PB83-187724

Draft Environmental Impact Statement for Standards for the Control of Byproduct Materials from Uranium Ore Processing (40 CFR 192)

(U.S.) Office of Radiation Programs
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The Environmental Protection Agency is proposing health and environmental protection standards for control of uranium and thorium tailings during ore processing operations and for final disposal. These standards would apply to tailings licensed by the U.S. Nuclear Regulatory Commission and the States under Title II of the Uranium Mill Tailings Radiation Control Act of 1978 (Public Law 95-604). This Draft Environmental Impact Statement examines health, environmental, technical, and cost considerations and other factors important to developing the proposed standards.

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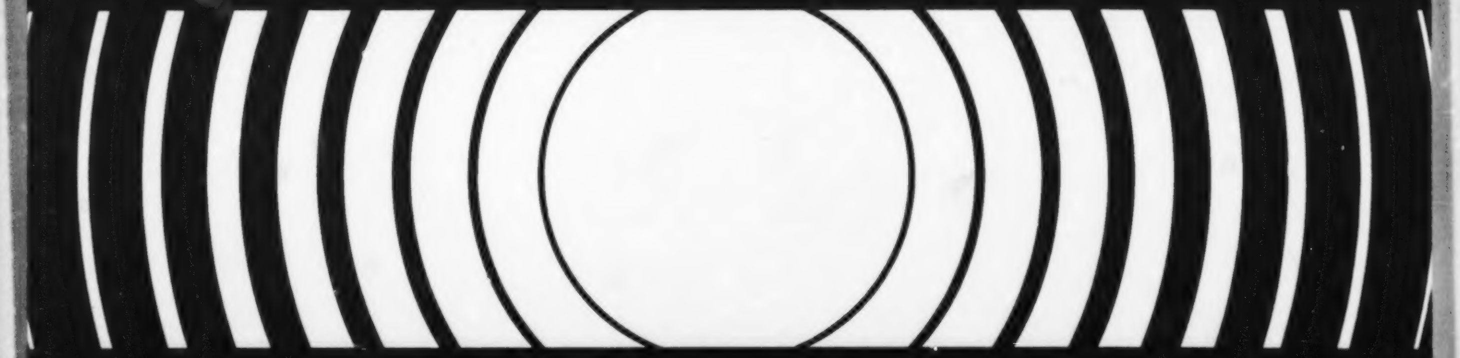

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Chapter 1: INTRODUCTION

In the Uranium Mill Tailings Radiation Control Act of 1978, Public Law 95-604, 42 USC 7901 (henceforth designated as "the Act"), Congress directed the Environmental Protection Agency (EPA) to "promulgate standards of general application for the protection of the public health, safety, and the environment from radiological and non-radiological hazards associated with the processing and with the possession, transfer, and disposal of byproduct material...at sites at which ores are processed primarily for their source material content or which are used for the disposal of such byproduct material." The term 'byproduct material' as defined by the Act means, for these sites, "...the tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content." The Act assigns the responsibility for implementation and enforcement of these standards to the Nuclear Regulatory Commission and its Agreement States through their licensing activities.

The Act also requires EPA to promulgate standards for cleanup and disposal of uranium tailings at inactive processing sites. EPA issued standards for cleanup of contaminated open lands and buildings and for disposal of tailings at inactive uranium processing sites on January 5, 1983 (48 FR 590).

1.1 Scope of Proposed Standards

Standards are required for the control of effluents and emissions from the tailings both during milling operations and for the final disposal of tailings. The Act specifies that standards for non-radioactive hazards must provide protection of human health and the environment consistent with applicable standards established under Subtitle C of the Solid Waste Disposal Act, as amended.

The sites that are affected by these standards currently include about two dozen conventional uranium mills and 4 heap-leaching locations; these sites are licensed by NRC or its Agreement States. Approximately 86 percent of all uranium produced in 1980 was produced from ore mined in underground or open-pit mines and processed in conventional uranium mills. Solution mining contributed 8 percent, and about 5 percent came from heap-leach plants, mine water extraction and conventional milling of low-grade stockpiles of ore.

Only conventional uranium mills and heap-leaching operations are covered by these proposed standards. Solution mining and phosphoric acid byproduct operations are not included because large amounts of tailing wastes are not involved in these operations. The Act was directed primarily toward the solution of environmental problems from the radioactive tailings piles resulting from conventional milling operations.

A number of environmental standards already apply to tailings. EPA promulgated 40 CFR Part 190, Environmental Radiation Protection Standards for Uranium Fuel Cycle Operations, on January 13, 1977 (42 FR 2858). These standards specify the radiation levels below which normal operations of the uranium fuel cycle must operate. Radiation exposures due to environmental release of and from uranium byproduct material are covered by these standards, with the exception of emissions of radon and its decay products. Under the Clean Water Act, EPA issued effluent limitations guidelines on December 3, 1982, for new source performance standards for wastewater discharges from the mining and dressing of uranium, radium, and vanadium ores (40 CRF 440, 47 FR 54598). Discharges of both radioactive and nonradioactive materials to surface waters from uranium byproduct materials are covered by these effluent guidelines. Because these guidelines and proposals have already been issued, we have not evaluated control measures for discharges to surface water in this DEIS.

EPA promulgated 40 CFR Part 261, Subpart F--Groundwater Protection, on July 26, 1982 (47 FR 32274) under the Solid Waste Disposal Act (SWDA), as amended by the Resource Recovery and Conservation Act. The Act requires that standards for nonradioactive hazards from uranium byproduct materials be consistent with standards promulgated under SWDA for such hazards. Also, the Act requires that the NRC establish general requirements which are, to the maximum extent practicable, at least comparable to requirements applicable to the possession, transfer, and disposal of similar hazardous material regulated by EPA under the SWDA. NRC Agreement States are required by the Act to adopt standards which are equivalent, to the maximum extent practicable, or more stringent than, standards adopted and enforced by the NRC. These responsibilities must be carried out by the NRC whether or not EPA promulgates standards for groundwater protection. We have included groundwater protection in this analysis to determine whether or not the SWDA standards should be supplemental or modified by the standards proposed under the Act.

Thorium mill tailings are included in the definition of byproduct material and must be licensed by the NRC or an Agreement State under the same provisions of the Act as uranium mill tailings. However, standards for thorium tailings are not included in this analysis because the only thorium currently being recovered from ore is as a secondary product at the W.R. Grace Co. facility near Chattanooga. There are also thorium byproduct materials at four inactive sites located in New Jersey, Illinois, Ohio, and West Virginia. The current demand for thorium is small, and there appears to be little growth potential. The two major uses of thorium are as a source material in nuclear applications and as a thin ceramic lantern mantle that gives off a bright light. Neither of these uses is expected to increase significantly in the next few years.

There are a few other licensed sites contaminated with uranium and thorium and their decay products. Two or three of these sites may contain uranium and thorium byproduct material as defined by the Act. These sites are not included in this analysis, because the quantities of material are relatively small and would not affect the overall analysis.

There are now about 170 million tons of tailings at the licensed mill sites. Of these, about 56 million tons were generated under government contracts. Most of these 56 million tons of tailings are not separated from other tailings and are commonly designated "commingled" tailings. The Department of Energy (DOE) has recently issued a report on commingled tailings in response to Congressional concern over whether the government or industry should pay for disposal of these tailings (DOE82). The analysis for these standards is not significantly affected by this issue. However, government sharing of costs would lead to a lesser impact on the industry, as reflected, for example, in fewer mills closing under certain alternatives for environmental requirements. Thus, government sharing of costs could permit application of more stringent standards. Our economic analysis assumes the total costs of compliance will be borne by the industry. Any government sharing of disposal costs would thus improve industry's economic position compared to that projected in this analysis.

1.2 Contents of the Analysis

In this document, we examine (1) alternative standards for disposal of uranium mill tailings, and (2) alternative standards for control of environmental releases from tailings during the operational phase of uranium mills. Both radioactive and nonradioactive releases are considered. Potential effects of tailings on health are estimated, along with the effectiveness and costs of different control approaches.

In Chapter 2 we briefly describe the uranium industry and summarize projections of uranium production to the year 2000. Chapter 3 contains a description of the uranium tailings themselves, with emphasis on their hazardous components and releases of contaminants to the environment. A model site and tailings pile is described in Chapter 4 for use in carrying out the analysis of benefits and costs of control. In Chapter 5, pathways through which radioactive and hazardous materials may cause exposure to man are examined. Based on the information in Chapters 4 and 5, potential health effects are estimated on local, regional, and national populations in Chapter 6. Chapter 7 contains a review of emission control measures for the operating period of the mill and estimates of the effectiveness and costs of these systems.

In Chapter 8 we examine the efficacy and longevity of the principal methods for disposal of tailings. Chapter 9 contains cost estimates for representative disposal methods for existing and future tailings at model sites. In Chapter 10 we analyze costs and benefits for tailings disposal standards options.

REFERENCES

DOE82 Department of Energy, "Commingled Uranium Tailings Study," DOE/DP-0011, June 1982.

Chapter 2: THE URANIUM MILLING INDUSTRY(1)

2.1 History of the Uranium Milling Industry

The uranium milling industry has undergone considerable change in the last 35 years, as uranium developed from a commodity of minor commercial use to one vital for nuclear weapons and for producing electrical energy. To meet military needs in the early 1940's, uranium ore was obtained from the rich pitchblendes (greater than 10 percent U_3O_8 equivalent) of the Belgian Congo and the Great Bear Lake deposits in Canada, supplemented by production from a few small mines in the Colorado Plateau area. These high-grade ores and concentrates were refined by an ether extraction technique adapted from analytical chemistry procedures. The processes used for low-grade ores were relatively crude and reflected little change from methods used at the turn of the century. Milling costs were high and uranium recovery was relatively inefficient.

After the Atomic Energy Act was passed in 1946, strong emphasis was placed on the discovery and development of new sources of uranium and on development of improved processing techniques. The Atomic Energy Commission (AEC) purchased 3×10^5 MT(2) of U_3O_8 between 1948 and 1970, with approximately 55 percent from domestic sources. Table 2-1 illustrates the size of the industry from 1948 to the present. During the peak production years of 1960 to 1962, there were up to 26 operating mills (excluding plants producing byproduct uranium from phosphates) with an annual production rate exceeding 1.5×10^4 MT of U_3O_8 from 7×10^6 MT of ore (average grade of 0.21 percent).

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(1) Much of the information in this chapter is based on the Nuclear Regulatory Commission's "Final Generic Environmental Impact Statement on Uranium Milling," NRC80, Chapters 2 and 3 and Appendix B. Material from other sources is separately referenced.

(2) Metric ton (MT) or 1000 kg, equivalent to 2200 pounds or 1.1 short tons (ST).

Table 2-1. Uranium Production(a)

Year	U_3O_8 (1000 MT)	Year	U_3O_8 (1000 MT)
1948	0.1	1965	9.5
1949	0.2	1966	9.6
1950	0.4	1967	10.2
1951	0.7	1968	11.2
1952	0.8	1969	10.5
1953	1.1	1970	11.7
1954	1.5	1971	11.1
1955	2.5	1972	11.7
1956	5.4	1973	12.0
1957	7.7	1974	10.5
1958	11.3	1975	10.5
1959	14.7	1976	11.6
1960	16.0	1977	13.6
1961	15.7	1978	16.8
1962	15.4	1979	17.0
1963	12.9	1980	19.8
1964	10.7	1981	17.5

(a) Adapted from DOE82. Includes U_3O_8 production obtained by mine water, heap-leaching, solution mining, or as a by-product of another activity.

Reduced military requirements and the slow development of commercial nulcear power resulted in fewer operating mills and lower uranium production in the period from 1963 to 1970. About 3.4×10^5 MT of U_3O_8 had been produced by the end of 1981, resulting in about 1.8×10^8 MT of tailings. Approximately 15 percent of the tailings are at 23 inactive mill sites covered under Title I of the Act, and the balance (85 percent or about 1.5×10^8 MT) is located at currently active mill sites considered by this analysis.

Mill capacities in 1978 ranged from 360 to 6300 MT of ore per day, with an average capacity of 1800 MT per day. In early 1978, 19 mills were operating; this increased to 21 in early 1980. Although there are several new mills proposed and some present ones are being shut down, these changes would not significantly alter the conclusions.

2.2 Conventional Milling Processes

In the uranium milling process, uranium is extracted from the crude ore and concentrated into an intermediate semirefined product called "yellowcake." The remainder of the material, essentially the total mass for low-grade ores, is disposed of in mill tailings piles. Most of the radioactivity associated with the ore goes to the tailings pile. This radioactivity consists primarily of radium and its decay products, which are not removed with the uranium during milling.

Historically, about 90 percent or more of yellowcake has been produced by conventional mills. In 1980 about 15 percent of yellowcake was produced from solution mining, mine water, copper dump-leach liquor, or wet process phosphoric acid effluents.

There are two basic conventional processes for removing uranium from ore: the acid-leach process and the alkaline-leach process. About 80 percent of the current milling capacity uses a sulfuric acid leach process. Since it is not economical to leach those ores having a high alkaline content with acid, these ores are leached with an alkaline solution. Several mills include circuits for both processes. Primary emphasis is placed on the acid-leach process in this analysis. Comments on the alkaline process are limited to differences between the processes that are pertinent to their environmental releases.

Figure 2-1 is a flow diagram of the process at a conventional mill leading up to the generation of waste tailings solids and liquids. In a conventional mill, the first step is grinding the ore to a size suitable for leaching out the uranium. Ore characteristics and the leaching process dictate the degree to which ore must be ground. For the acid leaching of sandstone ores, the ore is ground to the natural grain size.

Alkaline leaching requires much finer grinding. The ore is conveyed from the crushing circuit to the grinding circuit by belt feeders. Samples are taken at points between the crushing and grinding circuit for routine laboratory analysis. Rod and ball mills are usually used to grind the ore to approximately 28 mesh (600 microns) for the acid-leach process or to 200 mesh (74 microns) for the alkaline-leach process. The ores are wet ground (water added) with the aid of classifiers, thickeners, cyclones, or screens that size the ore and return coarser particles for further grinding, resulting in a pulp density of 50 to 65 percent solids. Water consumption is reduced by recirculating mill solutions (e.g., by recycling the clarified effluent from the grinding circuit thickener.) Wet milling can be used in place of both the crushing and fine grinding. This process uses a rotating steel cylinder. The tumbling action of the lifters, large pieces of ore, and a small charge of 8- to 10-centimeter steel balls are used to break down the ore.

After grinding, the ore is leached to remove uranium. In 1976, the acid-leach process was used by 82 percent of the industry. Acid leaching is preferred for ores with 12 percent or less limestone. Those with more than 12 percent limestone require excessive quantities of acid and, for economic reasons, are best extracted by alkaline leaching. The sulphuric-acid leaching process is compatible with several concentration and purification processes, including ion exchange, solvent extraction, or a combination of both processes. The

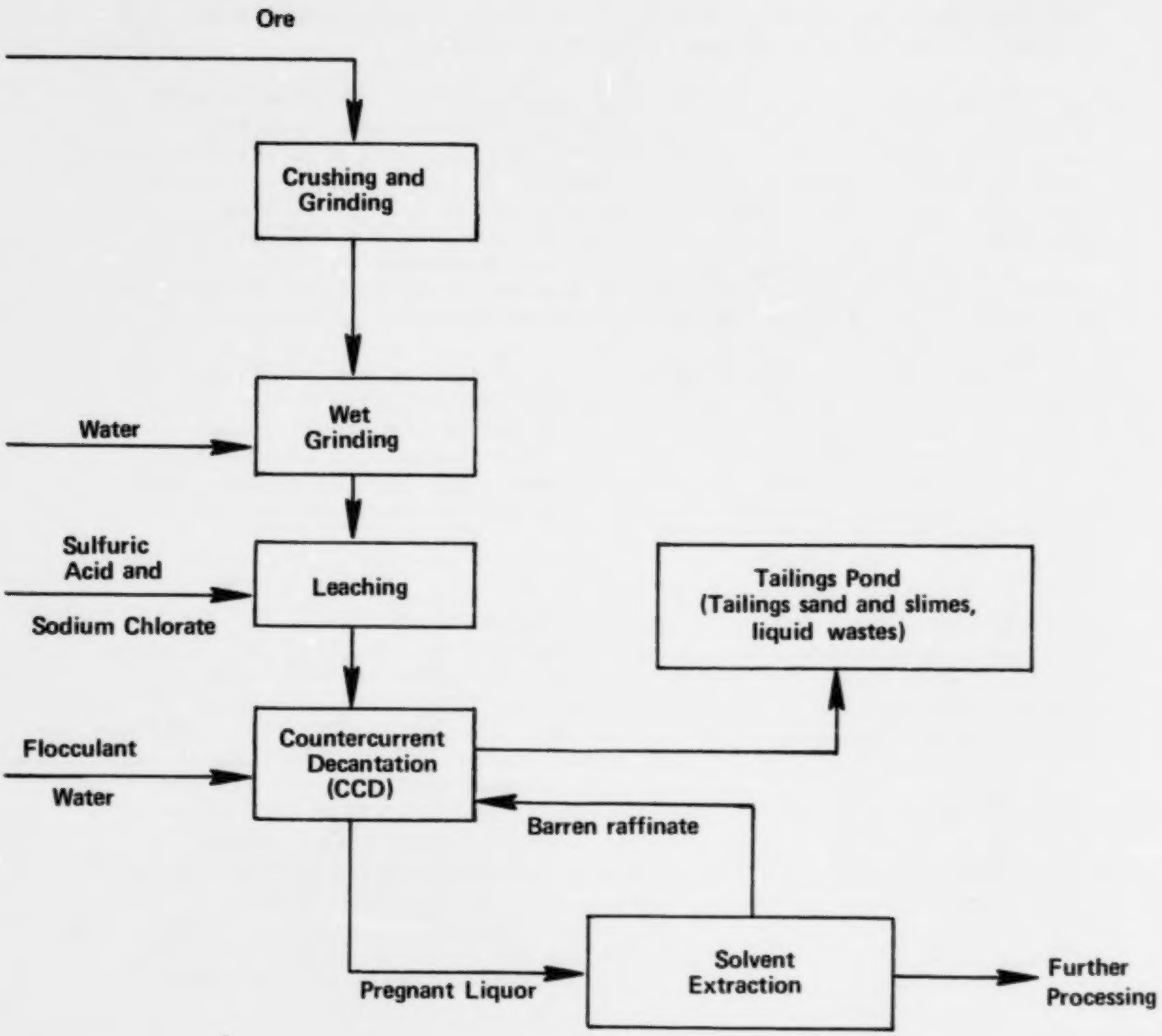
Ore
Crushing and Grinding
Water
Wet Grinding
Sulfuric Acid and
Sodium Chlorate
Leaching
Tailings Pond (Tailings sand and slimes, liquid wastes)
Flocculant
Water
Countercurrent Decantation (CCD)
Barren raffinate
Pregnant Liquor
Solvent Extraction
Further Processing

Figure 2-1. Flow Diagram of the Generation of Uranium Tailings Solids and Liquids from the Acid-Leach Process.

slurry from the grinding operation (50 to 65 percent solids) is discharged into the leaching circuit, which consists of several tanks in series. Sulfuric acid is continuously added to maintain the pH between 0.5 and 2.0. For U.S. ores treated exclusively for uranium extraction, acid consumption ranges from 20 to 60 kilograms of sulfuric acid per MT (40 to 120 lbs/tons) of ore.

An oxidant, either $NaClO_3$ or MnO_2, is also continuously added with the sulfuric acid to oxidize tetravalent uranium in the ore to hexavalent uranium, which is more soluble. Iron must be present in the solution for $NaClO_3$ or MnO_2 to be an effective oxidant for tetravalent uranium. Either oxidant acts to oxidize ferrous iron to the ferric state, and the ferric iron in turn oxidizes the uranium. Ore leaching proceeds at atmospheric pressure and a little above room temperature. Most of the uranium in the ore is dissolved, as well as some other materials, such as some uranium daughter products, iron, and aluminum. The residence time in the leaching tank is about 7 hours.

After ore leaching is completed, the "pregnant" leach liquor containing the dissolved uranium is removed from the tailings solids. This is carried out in a countercurrent decantation (CCD) circuit. In this operation, the slurry is first sent to hydrocyclones (liquid cyclone separators) that separate the coarse sand fraction as an underflow, and the sand fraction is subsequently washed in a series of classifiers. The overflows from the classifier and the hydrocyclone are combined, and the slimes are washed. Flocculants are added to promote settling of the suspended solids. The solids are washed with fresh water and recycled (barren) raffinate from the solvent extraction circuit. After thorough washing, the sands and slimes are pumped as a slurry to the tailings pond. After solid-liquid separation in the CCD circuit, the leach solution is sent to the solvent extraction and further processing.

The acid-leach and alkaline-leach processes have considerable chemical differences, and the ore is milled to a smaller size for carbonate leaching. However, this does not appear to cause any significant differences in environmental releases. A larger fraction of the thorium-230 is solubilized in the acid-leach process than in the carbonate-leach process, but the thorium is precipitated in the tailings pond when the acidity is reduced. Thus, except in the early stages of liquid discharges before the solution is neutralized, this difference is negligible.

2.3 Waste Management at Uranium Mills

During the early history of uranium milling, tailings liquids were discharged to surface waters. As late as 1975, Sears (Se75) noted that two mills were discharging liquid effluents to surface waters. In 1981, only the Uravan, Colorado, mill was still discharging treated liquid effluents directly to surface waters.

The alternative to discharging liquid effluent is the impoundment of both solids and liquids in a tailings pond. Initially, tailings ponds were located near the mill based on economics and accessibility. The pond areas were formed from dikes built with tailings sands or from soil and rock from the pond area. As the pond was filled, the dikes were raised with mill tailings sands, separated from the slurried waste with cyclone separators. This design was used for most of the inactive tailings piles (EPA80) and many of the older active piles. Current NRC regulatory practice discourages the use of tailings for dike materials (NRC80a, NRC77). However, this practice still continues for many of the existing active sites (e.g., Homestake and Kerr-McGee near Grants, New Mexico). Although the ponds were generally designed as evaporation ponds, there are instances where seepage has equaled or exceeded the evaporation rate (Ka75, EPA75). There are still seepage releases to groundwater and probably to surface water at several mills (See Chapter 3.)

It was not until 1976 that the NRC made a concerted effort to control uranium mill tailings. Performance objectives were issued in 1977 and again in revised form in Regulatory Guide 3.11 (NRC77). These objectives provide location criteria, require the elimination of windblown tailings, and require reducing post-reclamation gamma exposure to offsite areas to essentially background levels. Furthermore, this guidance discourages the use of upstream dam construction techniques (the dam is raised in stages on the tailings material) and specifies minimizing seepage from the tailings ponds by the use of clay or artificial liners. The guidance requires designs that improve the tailings stability and reduce the seepage from tailings disposal systems.

EPA collected information on active mills and waste disposal practices in 1978 (Ja79). Some of the notable conclusions are:

- Tailings and effluent disposal methods practiced in the United States generally consist of impoundment of mill wastes in unlined ponds. This disposal method is not state-of-the-art. It is usually inadequate, since up to 85 percent of the liquid effluent impounded may be lost by seepage and, subsequently, pollute groundwater.

- Treatment of mill effluents to reduce pollutant levels and/or to recover uranium or uranium byproducts is seldom practiced.

- Treatment and discharge as a method of effluent disposal is practiced at only one of the currently operating, conventional uranium mills in the United States.

- All effluent streams from the mills sampled in this study, were they to be discharged, would require treatment to comply with effluent limitation guidelines for point-source discharges. Currently, none of the streams sampled is being discharged.

- Unlined ponds, properly located, may be environmentally acceptable as a means of mill waste disposal under some local soil and hydrogeological conditions, because some native soils can mitigate the adverse effects of seepage, by exhibiting low permeabilities, thereby reducing seepage rates, and/or possessing characteristics that favor the uptake and fixation of seepage-borne contaminants.

- Total dependence on native soils above the water table for purification of seepage from unlined ponds is not technically sound, since uptake capacity is both unpredictable and time dependent, and anions such as sulfate, chloride, and nitrate are not removed.

- Lined ponds represent a recent advance in state-of-the-art technology for containment of millwastes, since they afford a greater degree of seepage prevention than unlined ponds and ensure protection of groundwater.

- Clay or treated clay liners are preferred for lining ponds containing mill tailings wastes.

After a mill ceases operations, the tailings impoundment will slowly dry up over a few years. In such a condition, tailings are continually vulnerable to spreading by wind and water erosion or by such uses as for fill around buildings. Some of these dry tailings piles have been the subject of a variety of stabilization schemes involving earth cover placement and revegetation. Stabilization attempts to date have not been generally successful, and none has been designed for the long term.

2.4 Uranium Recovery by Heap-Leaching

Most mills are not designed to process uranium ores of less than 0.04 percent U_3O_8. However, uranium is often extracted from such ores by a heap-leach process. Heap-leaching is also used when the ore body is small or situated far from the milling facilities. Shipping a high-grade solution or a crude bulk precipitate (the product of heap-leaching) to the mill is less expensive than hauling low-grade ore to the mill.

Uranium recovery by heap-leaching has been used for low-grade (0.01-0.03 percent U_3O_8) sandstone uranium ores. The ore to be heap leached is typically placed upon a gently sloped impermeable pad and saturated from above with a leaching solution. Pad impermeability is generally achieved by laying down a plastic sheeting, but other materials such as asphalt and concrete have been used on a pilot scale. Just above the pad, a network of pipes and drain tiles is put in place to collect the leachate that percolates to the bottom of the ore piles. The percolated leachate is collected and recirculated until the uranium concentration in the solution reaches 0.06 to 0.1 grams of U_3O_8/per liter. At this point the leachate is sent to resin ion-exchange columns for extraction of the uranium.

If mine water is used, uranium already in the water, as well as that extracted from the heap leach, is recovered. The most commonly used leach reagents are sulfuric acid and ammonium carbonate. In an efficient operation about 80 percent of the uranium will be extracted from the ore. Heap-leach piles are commonly about 100 meters long, 6 to 8 meters high, with beams separating the piles in segments about 20 meters wide. After completion of operations, the leached ore may be limed, graded, and stabilized by covering and revegetating the surface. A state-of-the-art heap-leaching operation is described in detail in a recent document (NRC78b).

2.5 Currently Licensed Uranium Mills

There were 27 licensed uranium mills, of which 16 were operating, in the United States as of September 1982. These mills are listed in Table 2-2. Edgemont, South Dakota, which is not an operating mill, has been included since it is licensed and has been excluded from the designated inactive sites (EPA80). The Tennessee Valley Authority (TVA) owns the site and had planned to reactivate the mill. However, TVA is now planning to clean up the site and move the milling operation. The Ray Point, Texas, site has also been shut down for several years. Eight mills closed during the period from January 1981 to September 1982. Another mill has been constructed and licensed, but it has never started operation. The data in Table 3-1 summarizes the operational features of the mills with significant tailings (NRC80a and Ja79, supplemented with private communications).

2.6 Future Uranium Supply and Demand

Uranium is required for both the nuclear power industry and defense activities. Projections of uranium needs for nuclear power can be reasonably accurate for the next 20 years, since 10 to 15 years is required from the decision to build a reactor until it is producing power. Power reactors ordered now will not be producing power until the 1990's. Uranium needs for defense purposes are much more difficult to project since they are greatly influenced by political considerations. However, it is likely that nuclear power needs will greatly

Table 2-2. Currently Licensed U.S. Uranium Mills[a]

Location	Owner
	OPERATING MILLS
Colorado	
Uravan	Union Carbide Corporation
Canon City	Cotter Corporation
New Mexico	
Milan	Homestake Mining
Ambrosia Lake	Kerr-McGee Nuclear
Texas	
Panna Maria	Chevron Resources
Utah	
Blanding	Energy Fuels Nuclear
La Sal	Rio Algom Corporation
Moab	Atlas Minerals
Washington	
Ford	Dawn Mining Company
Wyoming	
Gas Hills	Pathfinder Mines
Gas Hills	Union Carbide
Powder River	Rocky Mountain Energy
Powder River	Exxon Minerals
Red Desert	Minerals Exploration Co.
Shirley Basin	Pathfinder Mines
Shirley Basin	Petrotomics
	SHUT-DOWN MILLS
New Mexico	
Bluewater	Anaconda Minerals Company
Seboyeta	Sohio-Reserve
Church Rock	United Nuclear
Marquez	Bokum Resources
South Dakota	
Edgemont	Tennessee Valley Authority
Texas	
Falls City	Conoco-Pioneer Nuclear
Ray Point	Exxon (Susquehanna-Western)

(continued)

See footnote at end of table.

Table 2-2. Currently Licensed U.S. Uranium Mills[a]
(Continued)

Location	Owner
	SHUT-DOWN MILLS (Continued)
Utah	
Hanksville	Plateau Resources
Washington	
Wellpinit	Western Nuclear
Wyoming	
Jeffrey City	Western Nuclear, Inc.
Gas Hills	Federal-American Partners

[a] As of September 1982.

outstrip defense needs during the next 20 years. Thus, only demand for the nuclear power industry is projected in this analysis.

Projections of uranium demand are made for two cases. A "high" case is based on the mid-range nuclear generating capacity scenario of the U.S. Department of Energy (DOE) (DOE81). A "low" case is based on the DOE installed reactor capacity projection identified as the firm nuclear base scenario (DOE81). These estimates are presented in Table 2-3.

Yellowcake requirements are calculated by using the NRC assumptions given in their generic EIS for uranium milling (NRC80a). A conversion factor of 185 MT U_3O_8 in yellowcake per GWe-year is used. This assumes a 3 percent fuel enrichment, 0.20 percent tails assay, and an effective average nuclear generating plant capacity factor of 75 percent.

Conventional mills (as described in Section 2.2) are not assumed to satisfy the total demand for uranium. About 80 percent of the present uranium demand is supplied by conventional milling. This fraction is expected to vary during the next 20 years. The fraction of uranium assumed to be supplied by conventional milling is listed in Table 2-3 (NRC80a). The demand for conventional milling production, estimated by multiplying the total uranium demand by this fraction, is presented in Table 2-3 for the 20-year period 1980 to 2000.

Another important factor in projecting demand for uranium is the inventory held by utilities, reactor manufacturers, and fuel fabricators. A normal inventory level is about a 1-year level of consumption. Currently an abnormally large inventory of uranium is

Table 2-3. Projected Demands for Uranium Yellowcake

Year	Generating Capacity(a) (GWe) (High)	(Low)	Yellowcake Demand (1000 MT/y) (High)	(Low)	Fraction (High & Low)	Conventional Mill Demand (1000 MT/y) (High)	(Low)
1980	54	54	14.2	14.2	.884	12.5	12.5
1985	96	96	20	20.6	.790	16.6	16.3
1990	128	122	25.5	22.9	.714	18.1	16.3
1995	145	125	30.1	22.6	.747	22.5	16.9
2000	175	120	36.2	18.9	.784	28.4	14.8

(a)High--DOE mid-range nuclear capacity scenario. Low--DOE firm nuclear base scenario. (DOE80c)

Table 2-4. Projections of Demand, Production, and Inventory of Uranium Yellowcake (1000 MT/y of U_3O_8)

Year	Conventional Demand High	Low	Production High	Low	Ending Inventory High	Low
1980	12.5	12.5	13.8	13.8	48.9	48.9
1981	13.6	13.6	9.9	9.9	45.1	45.1
1982	14.9	14.9	9.4	9.4	39.6	39.6
1983	15.3	15.2	9.6	9.6	33.9	34.0
1984	16.0	15.8	10.6	10.6	28.5	28.8
1985	16.6	16.3	11.4	11.4	23.3	23.9
1986	17.3	16.8	12.9	12.7	18.9	19.8
1987	18.0	17.1	14.2	13.6	15.1	16.3
1988	17.9	16.7	15.8	14.6	13.0	14.2
1989	17.9	16.4	17.5	15.6	12.6	13.4
1990	18.2	16.3	19.2	16.5	13.6	13.6
1991	18.7	16.5	20.7	17.2	15.6	14.3
1992	19.2	16.6	22.2	17.7	18.0	15.4
1993	20.3	16.7	22.3	17.2	20.6	15.9
1994	21.4	16.8	23.5	17.6	22.7	16.7
1995	22.5	16.9	24.1	17.6	24.3	17.6
1996	23.5	16.8	26.0	17.9	26.8	18.7
1997	24.6	16.9	27.3	17.8	29.5	19.6
1998	25.8	16.1	28.6	17.2	32.3	20.7
1999	27.0	15.4	29.8	16.4	35.1	21.7
2000	28.4	14.8	31.0	15.7	38.4	22.6

being held. It is assumed that this inventory will be reduced to more normal levels over a 6-year period. This inventory reduction will result in less uranium production. These projections are shown in Table 2-4 for both high and low cases. The demands are from Table 2-3 and the production and inventory values are calculated using the 6-year inventory reduction assumption.

The total quantities of tailings produced by conventional milling from 1980 to 2000 is projected to be about 430 million tons for the high case and about 330 million tons for the low case. [The conversion factor used is 1,075 MT of tailing per MT of U_3O_8 as yellowcake (NRC80a) and assumes 0.1 percent uranium in ore, a 93 percent recovery rate during milling, and an average 85 percent mill capacity factor.]

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EPA80 Environmental Protection Agency, Office of Radiation Programs, 1980, "Draft Environmental Impact Statement for Remedial Action Standards for Inactive Uranium Processing Sites, 40 CFR 192," EPA 520/4-80-011, EPA, Washington, D.C..

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Chapter 3: ENVIRONMENTAL RELEASES FROM URANIUM MILLING WASTES

In this chapter, we discuss the composition of uranium mill tailings solids (sands and slimes), tailings pond liquids, and heap-leaching wastes. We also discuss the extent to which radioactive elements, toxic substances, and other contaminants from these wastes have been released to the environment through human activity and/or by natural causes. We defer to Chapter 4 the development of projections of releases from a model site.

3.1 Composition of Tailings Solids and Pond Liquids

Uranium mill tailings solids and pond liquids contain essentially all the radioactive and toxic elements of the original uranium ore, except for about 90 percent of the uranium which is extracted during the milling process. The tailings also contain a variety of chemicals used as part of the extraction process described in the previous chapter.

3.1.1 Radioactivity in Tailings

Most of the uranium recovered from ore is uranium-238, a radioactive isotope that decays, over billions of years, to become lead-206, a stable (i.e., nonradioactive) element. The lengthy decay process includes a number of intermediate stages (called decay products). These, too, are radioactive. Figure 3-1 traces the steps in this decay process. Since the ore was formed millions of years ago, uranium has continued to decay and an inventory of all of these decay products has built up. There are also radioactive materials from two other decay processes in uranium ore, the uranium-235 series and the thorium-232 series, but these are present in much smaller amounts, and we have concluded that it is not necessary to include them in our analysis (see Section 4.1).

When ore is processed most of the uranium is removed, and most of the subsequent decay products become part of the tailings. As a result, thorium-230 is the radionuclide with the longest half-life(1)

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(1) A half-life is the time it takes for a given quantity of a radioactive isotope to decay to half of that quantity. Figure 3-1 shows the half-lives of the members of the uranium-238 decay series.

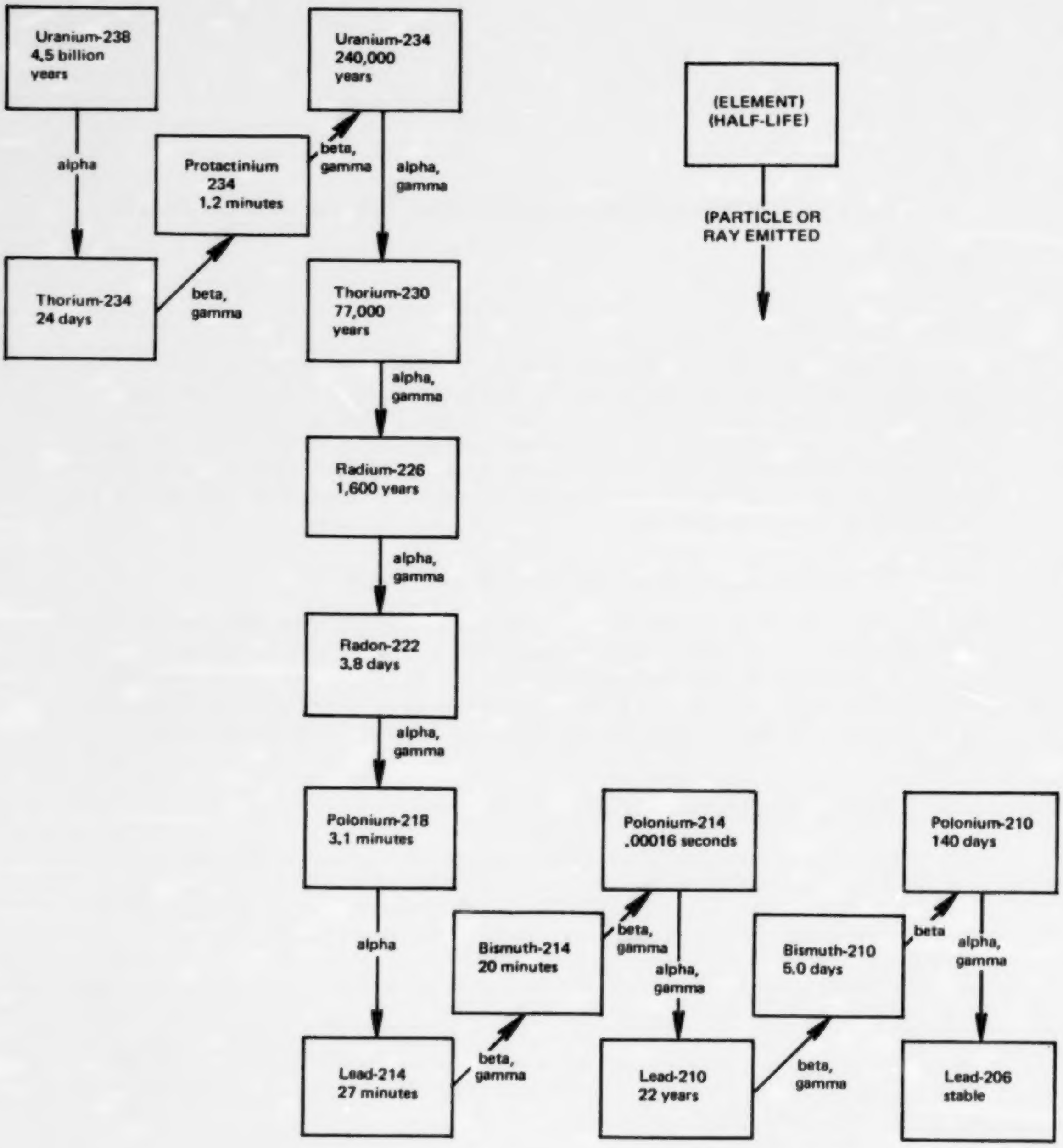
Uranium-238
4.5 billion years
alpha
Thorium-234
24 days
beta, gamma
Protactinium 234
1.2 minutes
beta, gamma
Uranium-234
240,000 years
alpha, gamma
Thorium-230
77,000 years
alpha, gamma
Radium-226
1,600 years
alpha, gamma
Radon-222
3.8 days
alpha, gamma
Polonium-218
3.1 minutes
alpha
Lead-214
27 minutes
beta, gamma
Bismuth-214
20 minutes
beta, gamma
Polonium-214
.00016 seconds
alpha, gamma
Lead-210
22 years
beta, gamma
Bismuth-210
5.0 days
beta
Polonium-210
140 days
alpha, gamma
Lead-206
stable
(ELEMENT)
(HALF-LIFE)
(PARTICLE OR RAY EMITTED

Figure 3-1. The Uranium-238 Decay Series.

of significance in tailings. Thorium decays to produce radium-226. Radium decays in turn to produce radon-222, a radioactive gas. Because radon gas is chemically inert, some of it escapes from the tailings particles in which it is produced, diffuses to the pile surface, and is carried away into the atmosphere. Airborne radon produces a series of short half-life decay products that are hazardous if inhaled. If the radon does not escape from the tailings, its decay products remain there, and the gamma radiation they produce may increase the hazard to people near tailings.

Since thorium-230 has a much longer half-life than its two immediate decay products, radium and radon, the amounts of radioactivity from radium and radon remain the same as that from thorium. The amount of radon released from a tailings pile, therefore, remains effectively constant on a year-to-year basis for many thousands of years, decreasing only as the thorium, with its 77,000-year half-life, decreases.

In Figure 3-2 we show how the yearly production rate of radon in a tailings pile will decrease with time. It falls to 10 percent of its initial value in about 265,000 years. This time scale illustrates the long-term nature of most of the significant radiological hazards associated with uranium mill tailings.

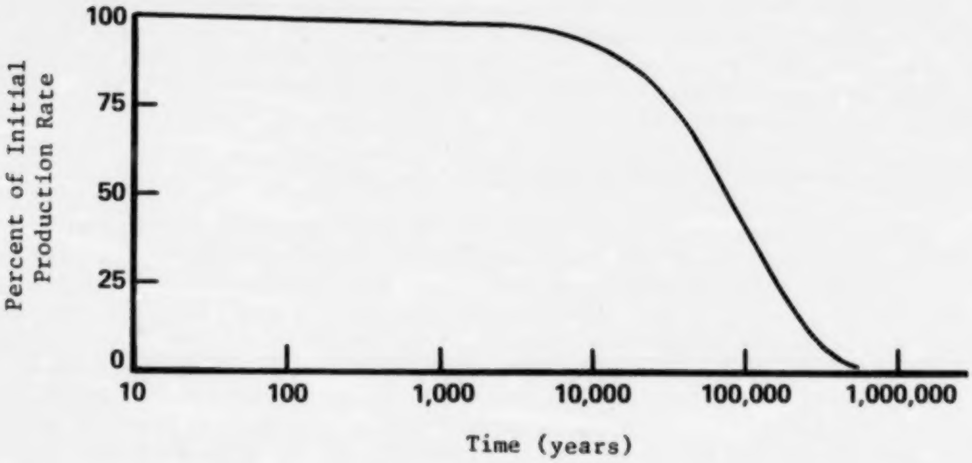

Figure 3-2. Radon Production in a Tailings Pile.

When discharged from the mill, tailings have both solid and liquid components. The solid portion of tailings is composed of particles ranging in size from coarse sands to fine slimes. In both the acid process and the alkaline process, the residual uranium and radium content of slimes is about twice that of sands. In the acid-leach process, about 95 percent of the thorium in the original ore remains with the solid tailings, while the balance is dissolved in the tailings liquids. Less than one percent of the radium is dissolved in the liquids. In the alkaline process, less than one percent of both the thorium and radium is dissolved in the tailings liquids.

In Table 3-1 we show, for licensed uranium mills (as of January 1980) with tailings piles, the quantity of tailings, area of the pile, average ore grade, and estimated average radium content in the solids. Also included are the estimated radon emissions from each pile and other factors relevant to emissions from tailings piles. Tailings at most future uranium mills are expected to fall within the range of values shown in Table 3-1. The ore grade at the different mills typically varies from 0.15 percent to 0.3 percent uranium, and the radium concentration (and presumably other radionuclides in the uranium-238 decay series) varies from 200 pCi/g to 900 pCi/g. This should be compared with the background radium concentration in average soil from 0.2 pCi/g to 3 pCi/g.

In Table 3-2 we have compiled selected available data on radioactivity and toxic element levels in tailings pond liquids. Many levels are more than two orders of magnitude above EPA drinking water standards (these are listed in Table 3-4), but large variations occur among the mills. The wide variation is caused by the characteristics of uranium ore and the process (i.e., acid- versus alkaline-leach). Again, the values in Table 3-2 are expected to characterize liquid wastes at future uranium mills.

3.1.2 Toxic Elements and Other Chemicals in Tailings

A number of toxic materials from ore or from chemicals used in processing have been found in both liquid and solid uranium mill wastes (Se75, FB76-78). The contaminants present depend on the ore source and the type of processing. In Table 3-3, we indicate the average concentration of 15 elements commonly found in the solids of 19 inactive tailings piles (Ma81a). The concentrations of these elements show wide variations among the piles, as well as wide variations above and below values for "typical soil." This data is believed to be representative of tailings at active mills as well as tailings to be generated at future mills. In Table 3-2, we showed the concentration of toxic substances and other chemicals in tailings pond liquids at existing uranium mills.

3.2 Routine Environmental Releases from Tailings

Releases from tailings wastes may occur to land, groundwater, surface water, and air. Land is contaminated chiefly by tailings transported by wind and water erosion; groundwater by the leaching of radionuclides, toxic elements, and other chemicals in solid tailings, or from seepage of tailings pond liquids; surface water from inputs from contaminated groundwater and also from runoff over contaminated areas; air from emissions of radon and fine wind-suspended tailings particles.

3.2.1 Air Contamination

Radon Emissions

In the uranium-238 decay series, radon is unique because it is a chemically inert gas and therefore freely migrates by diffusion from the tailings into ambient air. In Table 3-1 we show calculated radon emission rates(1) from the 27 active sites. These calculated rates range from 200 pCi/m^2s to 900 pCi/m^2s. Radon emission rates from uncontaminated soils are much lower, averaging close to 1 pCi/m2s, with a range of perhaps as much as a factor of 2 or 3 higher and lower. To estimate the annual radon release rates reported in Table 3-1, we assumed that the radon emission rate per unit area is 1.0 pCi/m^2s per pCi/g radium; this value was also used by NRC (NRC80, Appendix G). It is consistent with the assumption that the piles are dry, homogeneous, uncovered, and at least 3 meters deep. By way of comparison, Haywood (Ha77) has calculated values of 0.35, 0.65, and 1.2 pCi/m^2s radon per pCi/g radium for wet, moist, and dry tailings, respectively.

The radon release rates listed in Table 3-1 are likely to be greater than the actual release rates for active piles because these piles still contain significant quantities of entrapped water. Many active piles also contain large areas of standing water on their surface. Both conditions significantly inhibit the release of radon to air. In assessing the health impact from active tailings piles, we have considered the effect of the pond area in reducing radon emissions. However, with regard to assessing the impact of tailings piles when the mill is not active, we consider it more reasonable to assume that, over the time period of interest for the hazards associated with radon release (hundreds of thousands of years), the piles would be dry most of the time.

There have been few systematic ambient air measurements of radon emissions from tailings piles. However, studies to date (Mo82, PHS69) demonstrate good agreement between field measurements and the

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(1) The term emission rate is used rather than fluence rate or flux density, which, although more precise, are terms generally less familiar.

Table 3-1. Description of Mill Tailings Piles at Licensed Mills(a)

Location/ Company	Maximum Capacity (MT/day)	Ore Grade: Percent of U_3O_8	Tailings		Radium Concentration(b)(c) (pCi/g)	Estimated Radon Release(d) (kCi/y)	Type of Impoundment	Precipitation (in/y)	Evaporation (in/y)
			Amount (10^6MT)	Impoundment area (acres)					
COLORADO									
Canon City (Cotter)	1300	-	1.0	200	780	20	Unlined & lined	8	56
Uravan (Union Carbide)	1200	0.15	8.8	79	480	4.8	Unlined, collect seepage recycle or treat	11	47
NEW MEXICO									
Seboyeta (Sohio/Reserve Oil & Minerals)	1500	-	1.4	180	500	11	Lined with natural clay	8	56
Church Rock (United Nuclear)	3600	0.15-0.2	2.2	200	290	7.4	Unlined, dam failed	14	50
Bluewater (Anaconda)	6200	0.34	17.1	270	620	21	Unlined	8	56
Ambrosia Lake (Kerr-McGee)	6300	-	24.6	260	620	20	Some ponds lined with PVC	8	56
Milan (Homestake Mining Co.)	3100	0.2	17.9	200	385	9.7	2-section pond, unlined	-	-
SOUTH DAKOTA									
Edgemont (TVA)	500	0.2	2.8	123	560	8.9	11 ponds, half covered with soil	14	37
TEXAS									
Falls City (CONOCO/ Pioneer Nuclear)	2900	-	5.6	220	-	-	Natural clay	27	55
Panna Maria (Chevron Resources)	2200	-	1.2	250	-	-	-	-	-
Ray Point (Exxon)	800	0.18	1.7	49	520	3.1	-	-	-
UTAH									
La Sal (Rio Algom)	640	0.2	1.6	45	560	3.2	Unlined, dug into natural clay	12	62
Moab (Atlas)	1100	-	7.8	115	540	7.8	Unlined	8	64

See footnotes at end of table.

Table 3-1. Description of Mill Tailings Piles at Licensed Mills[(a)] (Continued)

Location/ Company	Maximum Capacity (MT/day)	Ore Grade: Percent of U_3O_8	Tailings Amount (10^6MT)	Tailings Impoundment area (acres)	Radium Concentration[(b)(c)] (pCi/g)	Estimated Radon Release[(d)] (kCi/y)	Type of Impoundment	Precipitation (in/y)	Evaporation (in/y)
WASHINGTON									
Ford (Dawn Mining)	400	0.3	2.8	106	850	11	Clay lined	12-18	50
Wellpinit (Western Nuclear)	1800	0.05-0.09	1.3	42	200	1.1	36 mil Hypalon liner	10-15	50
WYOMING									
Gas Hills (FAP)	900	-	4.2	105	420	5.6	2 ponds, unlined	10	42
Gas Hills (Pathfinder)	2500	0.15-0.26	5.5	75	420	4.0	5 ponds	9	45
Jeffrey City (Western Nuclear)	1500		11.0	85	430	4.8	-	10	36
Gas Hills (Union Carbide)	1200	0.15-0.18	7.6	150	310	5.9	Unlined	10	42
Powder River (Exxon)	2700	-	5.7	200	450	12	-	-	-
Powder River (Rocky Mt. Energy)	1800	0.15	8.0	150	420	8	Unlined	12	40
Shirley Basin (Pathfinder)	1600	-	4.2	150	540	10	-	-	-
Shirley Basin (Petrotomics)	1500	0.1	2.0	160	570	12	Bentonite clay	12	43
Total		-	146.0	3,537	-	191.3[(e)]	-	-	-

(a) As of January 1980, based upon "Environmental Study on Uranium Mills," TRW Inc., for U.S. Environmental Protection Agency, Contract #68-03-2560; "Final Generic Environmental Impact Statement on Uranium Milling," NRC, NUREG-0706, Appendix T; and relevant EIS's.

(b) Some values are not consistent with the reported ore grades if radium are and uranium are assumed to be in equilibrium in the ore.

(c) Also approximately equal to the estimated radon flux density in pCi/m^2-s.

(d) This is a maximum estimate obtained by assuming that the emanation from the tailings pond area is 1 pCi/m^2-s per pCi/g of radium-226. This relationship is well established for dry tailings (NRC GEIS, Appendix G), but the emanation from thoroughly wet tailings is insignificant. Therefore, the estimated emanation of active ponds should be reduced in proportion to the wetted area of the tailings.

(e) Does not include releases from piles where estimate was not obtained.

Table 3-2. Dissolved Substances in Tailings Pond Liquids at Selected Sites

Substance/ Units	Gas Hills[(a)] Wyoming (NRC77)	Moab[(b)] Utah (NRC79)	Gas Hills[(c)] Wyoming (NRC81)	Jeffrey[(d)] City Wyoming (NRC80)	Edgemont[(e)] S. D. (FB78)	Blue-[(f)] water N. M. (NM80)	Ambrosia[(g)] Lake N. M. (NM80)	Seboyeta[(h)] N. M. (NM80)	Church[(i)] Rock N. M. (NM80)	Milan[(j)] N. M. (NM80)
Radionuclides (pCi/l)										
Uranium-238	16,000	600	6,200	3,600	18,500	13,180	4,900	3,170	3,450	11,200
Thorium-230	170,000	50	-	250,000	26,000	-	-	-	-	-
Radium-226	420	-	-	35,000	1.7	620	106	110	58	68
Toxic Metals (mg/l)										
Arsenic (As)	42	7	12.1	-	2.75	2.25	4.23	1.27	1.55	5.02
Lead (Pb)	-	-	1.76	0.51	0.153	.75	2.61	2.07	0.71	0.006
Molybdenum (Mb)	-	-	-	0.41	0.23	0.6	23.3	.44	1.89	93.7
Selenium (Se)	-	-	-	0.01	0.456	2.35	1.74	1.53	0.27	36.7
Other Substances (mg/l)										
Iron (Fe)	--	-	145	5,450	-	-	-	-	-	
Manganese (Mn)	350	-	-	-	222.8		-	-	-	-
Sulfate (SO_4)	17,000	100,000	18,000	11,590	40,000	21700	27,000	31,600	15,100	7,430
Chloride (Cl)	1100	300	-	116	200	2,240	2,225	520	309	1,075
Total Dissolved Substances (TDS)	-	150,000	-	12,700	65,000	27,560	45,320	39,300	39,000	21,050
Acidity Index (pH)	acid	neutral	acid	3.5	2.01	1.51	1.33	0.97	1.33	10.2

[(a)] Owner: Pathfinder.
[(b)] Owner: Atlas.
[(c)] Owner: Federal American Partners.
[(d)] Owner: Western Nuclear.
[(e)] Owner: TVA.
[(f)] Owner: Anaconda.
[(g)] Owner: Kerr-McGee.
[(h)] Owner: Sohio.
[(i)] Owner: United Nuclear.
[(j)] Owner: Homestake Mining Co.

prediction of mathematical models. The data in these studies support the following conclusions:

- Radon levels immediately above tailings piles typically are above 10 pCi/l.
- At 0.5 km from some piles, radon concentration may exceed the average background by 1 pCi/l.
- Significant increases above background have been measured at distances up to 1.5 km downwind of tailings piles.

Emission of Tailings Particles

Tailings piles also release fine tailings particles to the air in moderate-to-high winds. Schwendiman, et al., have studied particle release rates from an active pile (Sc80). Their data show that for wind speeds from 7 mph to 25 mph, the airborne mass loading downwind from the pile is roughly 5×10^{-4} g/m^3. This is an order of magnitude greater than the mass loading measured just upwind of the site.

The airborne concentrations of several radioactive and toxic elements were also measured, confirming that the windblown particles from a tailings pile contain a variety of radionuclides, as well as the toxic elements selenium, lead, arsenic, mercury, and molybdenum. However, the air concentrations of toxic elements observed were well below the 8-hour threshold limit values to which workers can be repeatedly exposed without suffering adverse effects. (These values for occupationally exposed workers were established by the American Conference of Governmental Industrial Hygienists (AC81).) We conclude, therefore, that the primary hazard arises from breathing radionuclides, and their buildup on land surfaces.

3.2.2 Land Contamination

The action of wind and water can erode tailings from unstabilized piles onto nearby land. To determine the extent of this contamination at inactive sites, we conducted gamma radiation surveys at most of the inactive tailings sites in the spring of 1974 (Do75). We used the measured gamma radiation levels to estimate the extent of radium contamination in the surface soil (EPA80). If levels above 5 pCi/g, averaged over the top 15 centimeters, are considered to represent significant contamination, then, typically, windblown tailings have contaminated an area near each pile that is more than three times the area of the pile itself. It is reasonable to assume that, if uncontrolled, contamination at existing uranium mills will be comparable to that at inactive sites within a decade or so after the existing mills become inactive. Little data is available concerning contamination of land with windblown toxic materials. However, because

Table 3-3. Average Concentration of Elements Found in Inactive Uranium Mill Tailings(a)
(in ppm)

Tailings Pile	As Arsenic	Ba Barium	Cd Cadmium	Cr Chromium	Cu Copper	Fe Iron	Pb Lead	Hg Mercury	Se Selenium	Ag Silver	U Uranium	V Vanadium	Zn Zinc	Ra-226 Radium (x 10^{-6})
Arizona														
Monument Valley	1.5	-	-	-	-	-	--	--	0.064	--	60	1850	--	50
Tuba City	82	86	4	6	1160	7230	812	0.001	10	6	370	620	249	920
Colorado														
Durango	0.80	82	0.20	8.8	95	62	62	0.87	1.2	1.2	480	3900	304	700
Grand Junction	14	121	1.6	29	14	1170	50	0.026	3.1	0.72	180	1760	45	780
Gunnison	254	66	0.26	5.2	30	20800	137	--	1	3.8	90	80	120	420
Maybell	1.5	18	0.09	9.3	3.1	2100	13	0.09	13	0.15	120	120	17	274
Naturita	59	172	0.07	3.5	54	16400	48	--	0.47	1.1	500	2890	75	--
New Rifle	4.2	100	1.1	55	8	807	187	0.001	1.9	1.4	240	3990	31	870
Old Rifle	3.7	155	8.7	20	18	8250	38	0.25	2.7	0.46	380	520	359	1000
Slick Rock NC	34	453	0.027	4.9	35	6540	1250	109	0.76	1.7	80	620	21	780
Slick Rock UC	6.6	134	0.074	3.4	17	4080	29	0.074	2.2	0.57	50	1480	21	690
New Mexico														
Ambrosia Lake	2.6	96	3.6	8	58	90	--	0.002	68	0.15	210	1590	47	640
Shiprock	0.004	-	-	-	-	-	--	--	0.18	--	120	330	--	700
Utah														
Green River	1.9	73	0.40	17	102	1210	121	0.001	231	0.070	60	1390	21	810
Mexican Hat	63	12	0.70	1.0	488	3650	40	--	6	1.0	140	1350	57	780
Vitro Uranium(b)	210	2130	-	1010	310	31100	3060	--	--	0.022	180	100	340	
Vitro Vanadium(b)	244	3860	-	2030	1080	213000	350	--	--	0.066	50	830	350	900
Wyoming														
Spook	87	46	0.37	26	14	15299	2.5	--	262	2.2	130	350	31	340
Riverton	161	64	0.32	23	21	21800	3.2	--	391	2.4	70	240	38	560
"Typical" Soil(c)	6	500	0.06	100	20	38000	10	0.03	0.2	0.1	1.0	100	50	1.5

(a) Adapted from G. Markos and K.J. Bush, "Physico-Chemical Processes in Uranium Mill Tailings and Their Relationship to Contamination" (Ma81a).
(b) Two different parts of the Vitro Site, Salt Lake City, Utah.
(c) Bo66.

NC North Continent pile. UC Union Carbide pile.

whole tailings particles are transported, it is likely that the ratio of toxic materials to radioactive materials in contaminated land is in generally the same proportion as the ratio of these materials in the tailings. Surface runoff may also deposit tailings particles and, therefore, toxic materials in the vicinity of the pile. In these cases also, the amount of radioactivity should usually be a reasonably good indicator of the presence of elevated levels of toxic elements because like radioactive elements, they are, for the most part, relatively well fixed in tailings particles.

3.2.3 Water Contamination

Tailings can contaminate both surface and groundwater; we discuss what is known about each at both active and inactive tailings piles. As we shall see, the potential for water contamination at inactive piles is far less than the corresponding potential contamination at active sites.

Groundwater

Most of the potential for groundwater contamination arises from seepage of liquid waste from the tailings pile when the mill is active. Kaufmann, et al. (Ka75), estimated that 30 percent of the process water from two active tailings ponds in New Mexico had seeped into the ground. Purtyman, et al. (Pu77), estimated a 44-percent seepage loss from another pile in New Mexico during its active life. The NRC (NRC80) assumes that a model site will experience a 40-percent water loss by seepage and uses a mathematical model to estimate the movement of the seepage through unsaturated soil, formation of a seepage "bulb" in the saturated soil zone, and the movement of pollutants with groundwater. For its model mill in an arid region, where the evaporation rate far exceeds the precipitation rate, the NRC concluded that about 95 percent of the possible contamination of groundwater would be associated with the active phase of the pile and only 5 percent with with long-term loses from an inactive nonstabilized pile (NRC80). A more detailed description of groundwater contamination can be found in Appendix D.

Case histories showing water contamination problems near selected active uranium mills and mines are given in a recent report (UI80). Contamination that extends up to 8,000 feet from active tailings piles has been found, but this has been confined to shallow alluvial aquifers (UI80). Contamination of deep aquifers near these mills has not been observed. In Table 3-4 we have summarized the data from groundwater monitoring around these active tailings ponds. In general, the data support the following conclusions regarding the shallow aquifers:

- Unless pond water is contained by a natural clay or synthetic liner, contamination of groundwater near the pile may be expected. More than perhaps one-third of all active tailings piles show at least limited contamination of a shallow aquifer.

Table 3-4. Contamination in Shallow Aquifers Compared with Estimated Background Near Active Tailings Ponds[a]

Substance/ Units	EPA Drinking Water Standards[b]	Canon City, Colo.[c]		Ford, Washington[d]		Gas Hills, Wyoming[e]		La Sal, Utah[f]	
		Well (8000 ft)	Back-ground	Spring (4000 ft)	Back-ground	Monitoring Well	Back-ground	Monitoring Well	Back-ground
Radionuclides									
Uranium (Total - mg/L)	-	2.47	0.6	0.06	0.004	19.6	-	73	0.003
Thorium-230 (pCi/L)	-	1.6	-	-	-	110	-	80.1	
Radium-226 (pCi/L)	5.0	0.6	-	-	1.15	51.2	1.7-9.3	13.4	9.0
Toxic Metals (mg/L)									
Arsenic (As)	0.05	-	-	0.001	0.002	0.001	-	0.012	-
Lead (Pb)	0.05	-	-	0.005	0.016	0.3	-	0.001	-
Molybdenum (Mb)	-	16.7	1.1	-	-	-	-	0.04	-
Selenium (Se)	0.01	0.013	0.014	-	0.006	0.26	0.02	0.001	0.001
Other Substances (mg/L)									
Iron (Fe)	0.3	-	-	213	0-1.7	6.1	-	0.21	0.05
Manganese (Mn)	0.05	-	-	2.55	0.059	7	-	0.051	0.018
Sulfate (SO_4)	250	2720	-	5250	7.6	2932	120-271	4660	330
Chloride (Cl)	250	147	-	5.85	3.54	893	4.8-45	960	30
Total Dissolved Substances (TDS)	500	-	-	5836	202	5760	514-632	10,650	720

(a)Adapted from UI80.
(b)EPA primary and secondary drinking water standards.
(c)Process used: Acid and alkaline. Mill owner: Cotter Corporation.
(d)Process used: Acid. Mill owner: Dawn Mining Company.
(e)Process used: Acid. Mill owner: Union Carbide Corporation.
(f)Process used: Alkaline. Mill owner: Rio Algom Corporation.

- Contamination is accompanied by highly elevated levels of total dissolved solids, with sulfate being the chief constituent. Such water is rendered essentially useless for all puposes.

Because of the lack of background data on the aquifers and sites in question, no other general conclusions can be made. It is often difficult to prove that tailings are the cause of an elevated concentration of a substance in groundwater unless the background concentration of the aquifer is well characterized and there are no nearby potential sources of additional contamination. This situation is seldom realized. However, at one mill, heavy molybdenum contamination has been confirmed. Other sites show strong evidence of contamination from selenium and uranium (UI80).

There is evidence that groundwater in shallow aquifers is contaminated near some inactive sites, probably due to seepage of liquids from tailings ponds during and soon after their active use (Dr78). Groundwater contaminant concentrations near the inactive mills have been surveyed (FB76-78). Although it is not possible to positively ascribe the source of this contamination to tailings, some cases of elevated concentrations were found.

In Table 3-5, we summarize the toxic elements found in elevated concentrations in groundwater near inactive tailings piles. Markos has shown that many of the soluble elements in piles tend to precipitate and form a barrier when liquids move downward in the pile to the soil at the tailings-soil interface (Ma79a, Ma81b, Ma81c). This would prevent contamination of groundwater from tailings piles during the inactive phase. However, it is not known how long this barrier will last, and there could be channels through the barrier at locations other than those sampled. DOE is currently sponsoring additional studies of these potential routes of groundwater contamination.

Surface Water

Standing water with elevated concentrations of toxic materials has been reported on and adjacent to some tailings sites (Ma81c, FB76-78). Usually, these concentrations are intermediate between those reported for waters within piles and normal levels in surface water. Surface water runoff from rains and floods can wash surface salt deposits and tailings from an unprotected pile, causing spread of toxic and radioactive elements to nearby land and streams. A more likely route for the contamination of surface water is seepage of contaminated groundwater into a nearby stream or reservior. Some degradation of water quality in nearby streams has been reported at active sites. However, studies of the inactive tailings piles do not show that nearby streams are being contaminated (FB76-78).

Table 3-5. Elements Found in Elevated Concentrations in Groundwater Near Inactive Tailings Sites

Tailings Site[a]	Elements[b]
Gunnison, Colorado	Arsenic, Barium, Chromium, Iron, Lead, Selenium, Vanadium
Ambrosia Lake, New Mexico	Barium, Lead, Vanadium
Falls City, Texas	Arsenic, Barium, Chromium, Iron, Lead, Selenium, Radium, Vanadium
Green River, Utah	Arsenic, Chromium, Lead, Selenium
Ray Point, Texas	Arsenic

[a] (FB76-78).

[b] At most sites there are other potential sources of this toxic material contamination; see orginal reports for details.

3.3 Nonroutine Releases

3.3.1 Accidents and Acts of God

The most credible accident that could lead to a widespread release of tailings solids and pond water is a dam failure at a tailings pond. This actually occurred at the United Nuclear mill in Church Rock, New Mexico on July 16, 1979, and 100 million gallons of tailings-pond water and 1000 tons of solid tailings were released into the Rio Puerco, a large ephemeral stream. Following the spill, abnormally high concentrations of radionuclides and toxic elements were recorded as far as 36 miles downstream. However, after several weeks, water quality of the Rio Puerco susbstantially improved to within background levels of contaminants. In addition to surface-water contamination, some groundwater contamination in shallow wells adjacent to the Rio Puerco was also detected. Contaminated sediment was found in the Rio Puerco for several miles downstream of the spill.

The spill prompted a commitment of resources from several Federal and State agencies to study the failure and to monitor the contamination. At the urging of the State of New Mexico and the Navajo Nation, United Nuclear conducted a cleanup of contaminated areas and supplied the Navajos with replacement water. The ultimate cost of the entire incident will probably be several million dollars.

Although the Church Rock tailings-dam failure occurred spontaneously, natural events could also precipitate such a failure: most notably severe flooding or an earthquake. In Chapter 8, the probabilities of such events are discussed, along with engineering and site selection options for minimizing these probabilities. Also discussed in Chapter 8 are the impacts of events such as tornadoes and glaciation on the effectivness of contaminant controls.

3.3.2 Misuse of Tailings Sands

In the recent past, uranium mill tailings have been used extensively as a building material, chiefly as fill around and under foundations and concrete slabs. The tailings sands have ideal physical characteristics for this purpose. However, such use typically results in building occupants being exposed to high levels of radon decay products and thereby incurring a significant lifetime risk of lung cancer. In Grand Junction, Colorado, over 700 buildings have been identified as contaminated and requiring remedial action. In other mill towns, it is estimated that more than 350 buildings are contaminated. In addition to buildings, many thousands of other locations have been identified (e.g., sidewalks, lawns, gardens, driveways) in mill towns where tailings have been used. These buildings and locations were contaminated by tailings from inactive mills. We have not assessed the extent of existing misuse near active mills.

3.4 Environmental Releases from Heap-Leaching Operations

The principal solid waste from heap leaching is the barren material remaining after uranium recovery. Airborne emissions from heap-leaching operations include particulates suspended by wind erosion of the pile and radon gas. The particulates will contain toxic elements and radionuclides in proportion to the ore concentrations. The amount of radon and particulates given off will be proportional to the size of the operation. These have been calculated for the heap-leaching cell covering about 0.5 acre in area described in Chapter 2.

Particulate emissions from the dry portion of a heap-leaching cell are estimated to be about 1 MT annually. The radon emanation rate from this operation is calculated to be 25 Ci/y (NRC78). This is less than one-half as much as a tailings pile per unit acre.

Releases of contaminants to groundwater could result from the seepage of leachate containing elevated concentrations of radionuclides and toxic elements. This, however, would not normally pose a problem during operations since an efficient heap-leaching operation requires an impermeable pad and all leachate is collected for processing. After termination of operations, normal rainfall could lead to some leaching from the piles, but we expect this to be no greater threat than leaching from an unstabilized conventional tailings pile.

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Chapter 4: MODEL SITE AND TAILINGS PILE

This chapter summarizes the specific characteristics of the model site and tailings pile used for the analyses presented in Chapters 5 and 6.

4.1 Model Site

The "model mill" chosen for this analysis is the one developed for the NRC's Final Generic Environmental Impact Statement on Uranium Milling (NRC80). The model mill is based on features of uranium mills in operation in the 1970's. The characteristics, operating procedures, and effluents of the model mill were derived from data for existing mills as described in the technical literature and in environmental reports (MP80). Since the Act relates only to the tailings resulting from operation of the mill, the "model site" used for the analysis in Chapters 5 and 6 is defined as the area within a radius of 80 kilometers from the center of the model mill tailings pile.

4.1.1 Meteorology

The meteorology of the model site is typical of semiarid regions of the western United States. The average annual precipitation of the model site is 31 cm (12 inches). Potential evaporation exceeds precipitation, averaging 150 cm (60 inches) per year. Joint frequency of the annual average wind speed, direction, and atmospheric stability for the model site are presented in Table 4-1.

4.1.2 Demography

Two population distributions were used for the model site to represent a range of potential impacts from the model tailings pile: (1) the population distribution from the NRC model site (NRC80), and (2) the population distribution near the tailings pile in Edgemont, South Dakota (NRC81). The NRC model site represents a location where only a few people live close to the tailings pile (referred to here as a "remote" site). The Edgemont site represents a location with a larger population living near the tailings pile (referred to here as a "rural" site). Tables 4-2 and 4-3 present these population distributions as a function of distance and direction from the model tailings pile.

Table 4-1. Annual Average Joint Frequency Distribution for Winds in the Model Mill Region

Class/Speed(a) (m/s)	Wind Direction (Joint Percent and Frequency)																
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
ALL CLASSES	5.01	4.64	5.02	5.44	4.81	2.77	2.95	3.01	8.05	8.68	14.82	16.40	9.87	4.17	2.27	2.09	100.00
STABILITY CLASS A	0.11	0.17	0.14	0.08	0.05	0.03	0.03	0.05	0.14	0.12	0.14	0.22	0.25	0.27	0.14	0.08	2.02
0.0-1.5	0.06	0.10	0.08	0.05	0.03	0.02	0.02	0.03	0.08	0.07	0.08	0.13	0.15	0.16	0.08	0.06	1.20
1.6-3.2	0.05	0.07	0.06	0.03	0.02	0.01	0.01	0.02	0.06	0.05	0.06	0.09	0.10	0.11	0.06	0.02	0.82
STABILITY CLASS B	0.36	0.49	0.42	0.31	0.39	0.07	0.14	0.02	0.34	0.64	0.80	1.52	1.10	0.59	0.41	0.39	7.99
0.0-1.5	0.17	0.28	0.27	0.15	0.22	0.04	0.10	0.00	0.18	0.33	0.41	0.85	0.59	0.33	0.22	0.24	4.38
1.6-3.2	0.09	0.15	0.13	0.08	0.11	0.02	0.03	0.00	0.09	0.17	0.22	0.45	0.31	0.17	0.12	0.13	2.27
3.3-5.1	0.10	0.06	0.02	0.08	0.06	0.01	0.01	0.02	0.07	0.14	0.17	0.22	0.20	0.09	0.07	0.02	1.34
STABILITY CLASS C	0.55	0.64	0.67	0.67	0.44	0.08	0.14	0.13	0.72	1.07	1.93	2.10	1.88	0.79	0.35	0.38	12.54
0.0-1.5	0.08	0.11	0.14	0.11	0.06	0.00	0.02	0.02	0.12	0.10	0.20	0.21	0.26	0.10	0.06	0.05	1.64
1.6-3.2	0.20	0.26	0.34	0.26	0.14	0.01	0.06	0.05	0.29	0.23	0.45	0.52	0.62	0.25	0.14	0.11	3.93
3.3-5.1	0.24	0.24	0.14	0.30	0.23	0.07	0.05	0.06	0.25	0.52	0.74	0.85	0.71	0.34	0.10	0.21	5.05
5.2-8.2	0.03	0.03	0.05	0.00	0.01	0.00	0.01	0.00	0.06	0.13	0.43	0.31	0.23	0.10	0.05	0.01	1.45
8.3-10.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.09	0.21	0.05	0.00	0.00	0.00	0.43
Greater than 10.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.01	0.00	0.00	0.00	0.04

See footnote at end of table.

Table 4-1. Annual Average Joint Frequency Distribution for Winds in the Model Mill Region (Continued)

Class/ Speed[(a)] (m/s)	Wind Direction (Joint Percent and Frequency)																
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
STABILITY CLASS D	1.15	0.99	0.77	1.39	1.05	0.27	0.59	0.73	2.19	3.49	6.88	7.13	3.75	1.53	0.64	0.49	33.04
0.0-1.5	0.16	0.13	0.11	0.11	0.06	0.02	0.09	0.09	0.18	0.19	0.22	0.31	0.25	0.06	0.04	0.06	2.08
1.6-3.2	0.30	0.23	0.20	0.21	0.10	0.03	0.13	0.16	0.33	0.36	0.38	0.54	0.39	0.10	0.07	0.10	3.63
3.3-5.1	0.45	0.32	0.31	0.68	0.52	0.09	0.18	0.31	0.84	1.39	1.78	1.93	1.02	0.44	0.14	0.21	10.61
5.2-8.2	0.22	0.24	0.14	0.37	0.36	0.10	0.16	0.14	0.68	1.17	3.37	3.13	1.60	0.80	0.36	0.11	12.95
8.3-10.8	0.02	0.06	0.01	0.02	0.01	0.02	0.02	0.03	0.14	0.31	1.00	1.01	0.47	0.13	0.03	0.01	3.29
Greater than 10.8	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.02	0.07	0.13	0.21	0.02	0.00	0.00	0.00	0.48
STABILITY CLASS E	2.12	1.74	2.35	2.33	2.22	1.92	1.54	1.52	3.58	2.56	3.72	3.77	2.05	0.74	0.57	0.56	33.29
0.0-1.5	1.39	1.15	1.66	1.53	1.58	1.54	1.11	1.00	2.31	1.38	2.18	2.37	1.23	0.41	0.31	0.34	21.49
1.6-3.2	0.52	0.44	0.53	0.50	0.46	0.36	0.37	0.38	0.75	0.56	0.71	0.79	0.48	0.15	0.11	0.08	7.19
3.3-5.1	0.21	0.15	0.16	0.30	0.18	0.02	0.06	0.14	0.52	0.62	0.83	0.61	0.34	0.18	0.15	0.14	4.61
STABILITY CLASS F	0.72	0.61	0.67	0.66	0.66	0.40	0.51	0.56	1.08	0.80	1.35	1.66	0.84	0.25	0.16	0.19	11.12
0.0-1.5	0.45	0.37	0.47	0.42	0.42	0.25	0.31	0.32	0.64	0.43	0.65	0.79	0.40	0.10	0.06	0.07	6.15
1.6-3.2	0.23	0.17	0.14	0.14	0.18	0.13	0.16	0.17	0.31	0.15	0.30	0.37	0.24	0.07	0.06	0.06	2.88
3.3-5.1	0.04	0.07	0.06	0.10	0.06	0.02	0.04	0.07	0.13	0.22	0.40	0.50	0.20	0.08	0.04	0.06	2.09
5.2-8.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8.3-10.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Greater than 10.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(a) Frequencies for unlisted windspeed groups are 0.0 percent. The average windspeed for each interval is as follows:

Windspeed interval (w/s)	Average windspeed (w/s)
0. - 1.5	.671
1.6 - 3.2	2.46
3.3 - 5.1	4.47
5.2 - 8.2	6.93
8.3 - 10.8	9.61
Greater than 10.8	12.5

Table 4-2. Population Distribution at a Remote Uranium Mill Tailings Site

Distance	Wind Direction																
(km)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0.5 - 1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0 - 2.0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	8
2.0 - 3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.0 - 4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.0 - 5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.0 - 10.	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	8
10. - 20.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20. - 30.	1008	8	0	8	0	0	0	0	0	8	0	0	8	0	8	0	1048
30. - 40.	2000	500	0	8	0	0	0	0	0	0	8	8	0	0	500	500	3524
40. - 50.	0	0	13000	0	0	0	0	0	1000	8	0	0	0	0	1000	1000	16016
50. - 60.	0	0	3500	0	0	0	0	0	0	0	0	0	8	0	0	500	4008
60. - 70.	0	0	0	500	2000	0	0	0	0	0	2000	500	8	4000	0	500	9508
70. - 80.	0	0	0	0	0	0	0	0	0	0	8	1000	10000	12000	300	0	23308
Total																	57428

Table 4-3. Population Distribution at a Rural Uranium Mill Tailings Site

Distance (km)	Wind Direction																
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0.5 - 1.0	22	17	0	0	0	0	2	54	19	0	108	184	248	262	105	64	1085
1.0 - 2.0	81	76	8	0	0	0	0	0	3	54	79	80	343	162	27	10	915
2.0 - 3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.0 - 4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.0 - 5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.0 - 10.	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	129	144
10. - 20.	0	0	0	0	0	0	0	0	103	0	0	0	0	0	26	0	129
20. - 30.	0	0	0	0	0	0	0	190	0	0	0	0	0	0	0	0	190
30. - 40.	0	86	0	4725	0	0	0	14	0	0	0	193	0	0	0	106	5124
40. - 50.	0	1025	24	0	0	0	0	40	57	45	0	0	0	0	0	0	1191
50. - 60.	839	1615	3500	0	0	0	0	0	114	0	0	0	8	0	0	500	2568
60. - 70.	0	345	108	0	0	0	0	242	418	0	0	474	0	0	0	4033	5620
70. - 80.	560	857	0	0	0	0	0	1371	141	250	1495	182	0	0	0	0	4856
Total																	21822

4.1.3 Hydrology

The surface waters near the model pile are short-lived streams and small ranch impoundments used for livestock watering. These ephemeral streams have their maximum flows in June and July and are dry from September to February. Rivers and reservoirs are several miles away from the model pile. In some cases, the nearby surface water is good (of drinking water quality), but nearby surface water will contain relatively high concentrations of dissolved solids, making it unsuitable for many purposes. The groundwater resources near the model uranium mill tailings pile are an unconfined surface aquifer (often alluvial) plus deep aquifers separated from the surface by an impermeable layer. For calculating the movement of contamination from the model pile, the NRC assumed the water table (the top of the surface aquifer) is 25 meters below ground level. The deep aquifers often lie below 300 meters. The surface aquifer is the most commonly used, chiefly for domestic and stock water.

The deep aquifers are used for large industrial applications. Uranium mills, for example, often obtain mill process water from deep aquifers. Water quality of both the surface and deep aquifers is variable.

4.1.4 Agricultural Productivity

Uniform agricultural productivity rates for vegetables, meat, and milk in units of kg/y-km^2 were applied over the entire area of the model site except the controlled areas occupied by the mill and tailings pile. The production rates used are:

Product	kg/y-km^2
Vegetables	1020
Meat	1180
Milk	1140

These production rates are averages of production rates in States where uranium milling takes place (NRC80), weighted by the expected uranium development activity in each state.

4.2 The Model Tailings Pile

The tailings are assummed to be generated by an acid-leach mill. We generally assume the same characteristics as chosen by the NRC for their generic assessment of the uranium milling industry (NRC80).

4.2.1 Physical Description

The model tailings pile is typical of uranium mills in operation in the 1970's. The model mill generates 1800 MT of solid tailings slurried in water to about 50 percent solids by weight. When discharged from the mill, the slurried tailings material is pumped through pipes to the tailings pond impoundment. The pond is initially a square basin formed by building low earthen embankments. The initial embankment is assumed to be 3 meters high, 3 meters broad at the top, and 15 meters wide at the base. Each side of the square is assumed to be 947 meters long at the centerline of the embankment. The final embankments are assumed to be 10 meters high, 13 meters wide at the top, and 53 meters at the base; the initial centerline dimensions are unchanged. The total tailings disposal area is about 100 hectares (250 acres) of which 80 hectares contain tailings. It is assumed that, during operations, one-fourth of the tailings area is covered by water, and another one-eighth is wet.

After milling operations cease, it is assumed a few years pass before the tailings have dried and settled sufficiently to accommodate heavy equipment. The ultimate height of the tailings pile is assumed to be about 8 meters. In this post-operational phase, the emissions from tailings and the controls are different from those during the operational phase.

The principal physical characteristics of the model tailings pile are summarized in Table 4-4.

Table 4-4. Summary of Principal Physical Characteristics of the Model Tailings Pile

Parameter	Value
Operational life of tailings pile	15 years
Operating days per year	310
Dry solid waste generated (tailings)	1800 MT/day
Tailings density (slurry)	1.6 g/cm^3
Gross water flow to tailings pond	1800 MT/day
Tailings pond water recycled	30%
Net water consumption for tailings slurry	1260 MT/day
Area of tailings impoundment	100 ha
Area of tailings	80 ha
Ponded area on tailings (operational)	20 ha
Ponded area on tailings (post-operational)	0 ha
Wet beaches	10 ha
Average depth of tailings (post-operational)	8 m

4.2.2 Contaminants Present

The ore grade processed by the model mill from 1982 to 2000 is assumed to average 0.1 percent. The uranium recovery efficiency is assumed to be 93 percent. These values result in the tailings radioactivity listed in Table 4-5. Also listed are the assumed concentrations of toxic substances and other chemicals in the tailings pond liquids of the model pile (NRC80). The values in Table 4-5 are representative of tailings piles generated by acid leach mills. For an alkaline-leach mill, the most significant difference is that the concentration of thorium-230 in tailings liquids would be more than an order of magnitude lower.

4.2.3 Radioactive Emissions to Air

Radionuclides are released into air from tailings piles in the form of small dust particles and radon gas. Table 4-6 lists the assumed annual release rates of radionuclides from the model tailings pile. Particulate emissions are listed in two particle size distributions with characteristic diameters of 5 and 35 microns, respectively, and a density of 2.4 g/cm^3. The Activity Median Aerodynamic Diameters (AMADs) for these particle size distributions are 7.75 and 54.2 μm, respectively. A detailed description of the methods used for estimating these release rates is given in Appendix G-1 of the Generic Environmental Impact Statement on Uranium Milling (NRC80).

4.2.4 Emissions of Contaminants to Water

For the model pile, it is assumed that there are no routine releases to surface water. This is achieved through proper siting of the pile along with the minimal engineered controls required to substantially eliminate surface water runoff from the tailings pile.

The assumed routine emissions to groundwater are more substantial. NRC calculates a seepage rate of 0.22 million MT of water per year during the operational phase, and 5 percent of this value during the post-operational phase. We have made no estimates of the specific contaminants released with this water because they will vary with the ore used, the milling process, the geochemistry of the soil, and other factors.

Table 4-5. Chemical and Radiological Properties of Tailings Wastes Generated by the Model Mill(a)

Parameter	Unit	Value(a)
Dry Solids		
U_3O_8	wt%	0.007
Uranium (natural)(b)	pCi/g	39
Radium-226	pCi/g	280
Thorium-230	pCi/g	280
Tailings Liquid		
pH		2
Aluminum	mg/L	2,000
Ammonia	mg/L	500
Arsenic	mg/L	0.2
Calcium	mg/L	500
Cadmium	mg/L	0.2
Chloride	mg/L	300
Copper	mg/L	50
Fluoride	mg/L	5
Iron	mg/L	1,000
Lead	mg/L	7
Manganese	mg/L	500
Mercury	mg/L	0.07
Molybdenum	mg/L	100
Selenium	mg/L	20
Sodium	mg/L	200
Sulfate	mg/L	30,000
Vanadium	mg/L	0.10
Zinc	mg/L	80
Total dissolved solids	mg/L	35,000
Uranium (natural)	pCi/L	3,300
Radium-226	pCi/L	250
Thorium-230	pCi/L	90,000
Lead-210	pCi/L	250
Polonium-210	pCi/L	250
Bismuth-210	pCi/L	250

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[a] (NRC80).

(b) A 1.5 microgram mass of natural uranium has activities of 0.49 pCi each of uranium-238 and uranium-234 and 0.023 pCi of uranium-235.

Table 4-6. Radioactive Emissions to Air from Model Tailings Pile

Radionuclide	Operational Phase		Post-Operational Phase	
	Particulate Emissions,(mCi/y)			
	Particle size			
	5 μm	35 μm	5 μm	35 μm
Uranium-238	2.6	6.1	4.2	9.8
Uranium-234	2.6	6.1	4.2	9.8
Thorium-230	36	84	58	134
Radium-226	36	84	58	134
Lead-210	36	84	58	134
Polonium-210	36	84	58	134
	Gaseous Emissions (Ci/y)			
Radon-222	4400		7000	

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Chapter 5: ENVIRONMENTAL PATHWAYS

In this Chapter the pathways through which radioactive and toxic materials from mill tailings may cause exposure of man are examined and, where possible, quantified. While consideration of the impact of tailings piles on man depends on the status--operational or postoperational--of the mill, the contaminants which are expected to be present are the same. The projected health impacts of these materials are developed for the various pathways in Chapter 6, using the results obtained in this chapter for the model site.

5.1 Contaminants

The pathway analysis considers three general forms of contaminants. They are particulates (dust), radon (gas), and liquids (leachate). An introductory discussion of each form is given first, and the actual transport mechanisms are presented in the following sections. The model mill has been described in Chapter 4. The source terms and other model parameters are more fully described in the Final Generic Environmental Impact Statement on Uranium Milling (NRC80). Since the Act addresses only the tailings resulting from mill operations, only the model mill source terms applicable to the tailings pile are employed.

5.1.1 Particulates

The mechanism of movement of tailings particles by wind is similar to the movement of soil and is dependent on wind velocity, physical properties of the tailings, and the nature of the tailings surface. Wind forces can generate three basic modes of particle movement: surface creep, saltation, and airborne suspension. Surface creep, which spreads the tailings pile, involves particles ranging in size from 500 to 1000 μm. These particles are rolled along the surface by the push of strong winds and the exchange of momentum after impact with smaller particles in saltation. Saltation causes individual particles to jump and lurch within a few centimeters of the ground. Particles that saltate are from 100 to 500 μm in size, depending on shape and density, and are quickly brought back to the ground by gravitational force. The resulting exchange of momentum with other particles can initiate surface creep, saltation, or suspension. Particles in suspension are small enough (less than about 100 μm) to have a gravitational velocity of fall lower than the upward velocity of the turbulent wind. These particles may be carried through the atmosphere for long time periods and to distances far from their original location. While airborne, these suspended particles contribute to the inhalation pathway of exposure of man; when deposited, they contribute to the ingestion and external surface exposure pathways.

5.1.2 Radon

As shown in Figure 3-1, the radon decay process involves seven principal decay products before ending with nonradioactive lead. The four short half-life radioactive decay products immediately following radon are the most important sources of cancer risk. These decay, for the most part, within less than an hour. Members of the decay chain with relatively long half-lives (beginning with lead-210, which has a 22-year half-life) are more likely to be ingested than breathed and pose much smaller risks.

The principal short half-life products of radon are polonium-218, lead-214, bismuth-214, and polonium-214. Polonium-218, the first decay product, has a half-life of just over 3 minutes. This is long enough for most of the electrically-charged polonium atoms to attach to microscopic airborne dust particles that are typically less than a millionth of a meter (μm) across. When breathed, these small particles have a good chance of sticking to the moist epithelial lining of the bronchial tubes in the lung.

Exposure to radon decay products is expressed in terms of a specialized unit called the Working Level (WL). A Working Level is any combination of short half-life radon decay products that emits 130,000 million electron volts (MeV) of alpha-particle energy in 1 liter of air. The unit of cumulative exposure to radon decay products is the Working Level Month (WLM), which is exposure to air containing 1 WL of radon decay products for a working month, which is defined as 170 hours. (These units were developed to measure radiation exposure of workers in uranium mines.) Continuous exposure of a member of the general population to 1 WL for 1 year is equivalent to about 27 WLM. For exposures occurring indoors, we assume a 75 percent occupancy factor. Thus, an indoor (residential) exposure to 1 WL for 1 year is equivalent to about 20 WLM (EPA79a).

5.1.3 Liquid Contaminants

Airborne transport of tailings, with subsequent deposition on the ground and on surface waters, and transport or leaching of tailings by water used for drinking or irrigation can lead to exposure of man to radioactive and toxic substances. Future contamination of surface or groundwater is also likely if there is erosion of toxic elements from a pile by rain, by flooding, or, possibly, by the flushing action of seasonal changes in the water table when it can reach a pile from below. Severe floods have a greater, but difficult to evaluate, potential for producing significant contamination of streams and rivers. Future groundwater contamination from the seepage and flushing action of seasonal changes in the water table is uncertain. The degree of detail with which we can accurately treat these potential pathways varies. Modeling of water pathways requires site-specific data on sources and uses of water. The existence of actual water pathways for radioactive and toxic materials from tailings piles has not yet been verified, so we discuss these pathways in general terms only. Concentrations of dissolved substances in the tailings pond water at the model mill are shown in Table 4-5.

5.2 Atmospheric Transport

Airborne particulates and radon are analyzed using essentially the same calculational procedure. For the purpose of evaluating environmental impact, the analysis has been performed for both regional and national populations, using appropriate meteorological models for each. Because of the short half-life of radon, the worldwide impact is not significantly greater than the sum of the impacts of these two groups, and is therefore not calculated for this analysis. The term "regional" is defined to include local and regional populations at distances up to 50 miles (80 km) from the tailings site and "national" to cover the remainder of the contiguous United States.

5.2.1 Near the Tailings

We estimated radon concentrations over and close to the edge of generic, uncovered tailings piles, which, for calculational convenience, we take as circular in shape. For these calculations we assumed that the radon emission rate is a uniform 280 pCi/m^2s from the tailings. Concentrations for other emission rates would be proportionately higher or lower. The concentration calculations were made using generic wind data from the NRC GEIS (NRC80) and the AIRDOS-EPA dispersion model (EPA79b).

5.2.2 Regional

Meteorology

Airborne transport within the region is governed by meteorological conditions at the model mill site. These are detailed in Chapter 4. The transport mechanisms considered are described below.

Dispersion

The AIRDOS-EPA code (EPA79b) uses a modified Gaussian plume equation to estimate airborne dispersion of radionuclides from the pile. Calculations are site-specific and require detailed knowledge of the joint wind direction, wind speed, and stability frequencies. Since the accuracy of these projections decreases with distance, we limit calculations with this method to regional (less than 50 miles distant) locations. Values calculated are annual averages, since we are not concerned with diurnal or seasonal variations.

Deposition

AIRDOS-EPA estimates the annual average concentration of each radionuclide in air at ground level (corrected for deposition) as a function of direction and distance from the source. Deposition rates at each location are calculated for each radionuclide, and from these, the ground concentration levels at the desired locations. The radionuclides are deposited on the ground in the model by both precipitation and direct dry deposition.

Ingrowth of Radon Decay Products

At the point where radon diffuses out of the tailings, the atmospheric concentration of associated radon decay products is zero, because those decay products generated prior to diffusion from the surface have been captured in earth. As soon as radon is airborne, atmospheric decay product ingrowth commences and a secular equilibrium between the amount of radon and the amount of each decay product is approached. At such secular equilibrium, there is equal activity of all the short half-life radon decay products in air, and alpha radiation per unit of radon concentration is maximized. To account for incomplete equilibrium before this state is achieved, we define the "equilibrium fraction" as the ratio of the potential alpha energy from those decay products actually present to the potential alpha energy that would be present at complete equilibrium. As radon and its decay products are transported by the wind, the equilibrium fraction increases with distance from the pile. Depletion processes, such as dry deposition or precipitation scavenging, selectively removes decay products (but not radon), so complete equilibrium with the radon is seldom, if ever, reached.

When radon enters a structure, it remains for a mean time that is inversely proportional to the ventilation rate and proportional to its half-life. Since the former is much smaller than the latter, the building ventilation rate is a principal factor affecting further changes in the equilibrium fraction. It can also be affected by other considerations, such as the indoor surface-to-volume ratio and the dust loading in indoor air (Po78). We assume a 70-percent equilibrium fraction for indoor radon and its decay products.

We have also assumed that, on the average, Americans spend approximately 75 percent of their time indoors, mostly in their homes (Mo76, Oa72). We have weighted the indoor and outdoor equilibrium fractions for a given location by factors of 0.75 and 0.25, respectively, to estimate an effective value for calculating exposure to radon decay products from tailings piles. Since indoor exposure is the dominant form of exposure due to radon, this effective equilibrium fraction does not depend strongly on the distance from the tailings pile.

5.2.3 National

The inert radon gas emitted from tailings piles can be transported beyond the 50-mile regional cutoff. A trajectory dispersion model developed by NOAA (Tr79) has been used to estimate the national impact of radon emissions from the model pile. This model calculates the potential radiation exposure to the United States population for radon released from four typical mill site locations. (Descriptions of these typical mill sites--Casper, Wyoming; Falls City, Texas; Grants, New Mexico; and Wellpinit, Washington--are given in (Tr79).) Only exposures taking place beyond the 50-mile regional limit are considered. Details of the model are given in He75. The model yields radon concentrations (pCi/L) in air which were converted to decay product concentrations by assuming that 100 pCi/L of radon corresponds to a decay product concentration of 0.7 WL.

5.3 Hydrological Dispersion

There are two basic types of water resources considered in the impact assessments: (1) surface water (water on the surface of the earth, such as in lakes and rivers) and (2) groundwater (water occurring below the surface of the earth in a zone of saturation). The impacts on these two types of water resources in the model region are discussed in the following subsections for the case of an unlined tailings disposal area.

5.3.1 Surface Water

Operational

During operation of the mill, seepage from tailings ponds could add heavy metals, suspended solids, radioactive contaminants, and soluble salts to surface waters. Three routes of contamination might occur as a result of this seepage:

1. Seepage water from the tailings pond could intercept an aquifer and contaminate groundwater. This contamination could also degrade surface water quality under certain conditions. Irrigation wells or water supply wells could also penetrate aquifers that have been contaminated by seepage from tailings ponds. Water pumped from such wells would normally discharge into a surface water irrigation ditch or canal and ultimately into a stream. Contaminated water extracted via such wells would remain contaminated when it entered a surface water stream.

2. Seepage water could form surface pools downgrade from the tailings pond. Consideration of the transport time and concentration data for the seepage pools indicates that the trace materials in the pools would have the same initial composition as the tailings pond. This surface water would be subject to a high rate of evaporation,

which would result in a concentration of the soluble ions as the volume of seepage water decreases. During periods of local precipitation and spring runoff, this contaminated water could enter surface streams or rivers.

3. During dry periods, seepage water might reach the ground surface and be subject to a high evaporation rate, which would result in salt deposits. These areas would be exposed to surface runoff during periods of precipitation or during periods of snowmelt, at which time the precipitates again would be subject to dissolution and transport, resulting in a pulse of contaminated water reaching surface waters. Depending on the amount of materials in the runoff and the dilution capacity of the existing streamflow, the water quality of some streams, on rare occasions, could reach toxic levels.

Post-Operational

After mill operations cease, seepage from the tailings would be substantially reduced since discharge of water from the mill ends. The permanent seepage rate caused by precipitation falling on uncovered, abandoned tailings is estimated to be about 5 percent of the rate during the 15-year operational period (NRC80).

5.3.2 Groundwater

The impacts of uranium milling operations on groundwater are generally site-specific (because of regional and local variations in geology and hydrology) and thus are difficult to discuss on a generic basis. For illustrative purposes, however, a set of geological and hydrological characteristics has been assumed for the model region.

The effects of mining on groundwater can be fairly extensive and in many cases cannot be logically separated from the effects of nearby milling operations. For the model mill, however, we assume that the mines will be sufficiently far from the tailings pond to have no effect on effects due to tailings pond seepage.

Operational

By far the greatest impact on groundwater resulting from operation of a model mill would be from seepage from the tailings pond. The term "tailings pond" is used in the general sense in this context, and is intended to include evaporation ponds or any other type of unlined facility which receives mill waste water. The model mill contains an unlined tailings disposal area. The principal contaminants in the acidic tailings pond liquid are radium, thorium, sulfate, iron, manganese, and selenium (Table 4-5).

Post-Operational

After mill operations cease, seepage from the tailings would be substantially reduced because of the cessation of discharge of water from the mill. It should be emphasized that this analysis assumes that no new wells are permitted which would withdraw contaminated groundwater from the aquifer affected by the seepage.

During the post-operational period, an advancing front of seepage water containing nonradioactive contaminants would be moving downgradient. In this analysis, contaminant concentrations have been calculated on the assumption that there would be no lateral dispersion; this is a conservative assumption in that it results in overestimation of downgradient concentrations of contaminants. As these contaminants disperse downgradient, their concentrations would be reduced.

5.4 Environmental Concentrations

We calculate environmental concentrations, radiation doses, and health risks due to airborne releases using three computer codes--AIRDOS-EPA (EPA79b), RADRISK (Du80), and DARTAB (Be81).

AIRDOSE-EPA estimates, for a given source term, the amount of intake of each radionuclide, or the external concentration, at the point of exposure. RADRISK calculates the radiation dose and risk from unit intake of a given radionuclide. DARTAB is a control code that scales the unit estimates of RADRISK to match the actual exposure levels calculated by AIRDOS-EPA and then displays the results in a useful format.

5.4.1 Calculational Procedures

The regional environmental concentrations resulting from airborne emissions presented in this Chapter are obtained using the AIRDOS-EPA code. The RADRISK and DARTAB health risk calculations are described in Chapter 6 and Appendix C.

The AIRDOS-EPA code was developed for EPA by the Oak Ridge National Laboratory. It is a modification of AIRDOS-II, a code in use for many years, also developed by ORNL. Terrestrial food chain models used by the code are based on those used by the U.S. Nuclear Regulatory Commission, as provided in Regulatory Guide 1.109.

A modified Gaussian plume is used to estimate dispersion of as many as 36 radionuclides from point or area sources. Radionuclide concentrations in air, rates of deposition on ground surfaces, ground surface concentrations, and intake rates due to inhalation and ingestion (meat, milk, fresh vegetables) are then calculated. Meteorological, population, and other data characteristics of the site can be used to give more accurate assessments of a specific source.

When a source continually emits long half-life radionuclides, the environmental concentration levels build up for as long as the source continues to emit. This is not a significant consideration for air concentrations, but is for those concentrations which result from deposition on the ground surface. Our calculations assume that the particulates which deposit on the ground surface are removed by environmental processes, such as leaching, at a rate of 2 percent per year. (In addition, only 20 percent of the radon which results from the decay of deposited radium is assumed to escape). Since the environmental concentrations are not constant, they are calculated for specific times appropriate to the analysis. For the operational period, this is at the end of 15 years (the expected duration of mill operation) for the assessment of individual exposure and at the end of 100 years for the assessment of population exposures. The release rates used for these calculations are those shown in Table 4-6.

For the post-operational period, the enviromental concentrations are calculated at the end of 100 years of releases. The release rates for this period assume the tailings pond no longer exists and that the entire tailings pile area (80 ha) contributes to the releases. Because of the 2 percent per year removal rate assumed for deposited particulates, these concentrations are close to equilbrium.

Radon decay product concentrations (WL) are calculated from the atmospheric radon concentration (Ci/m^3) using an effective equilibrium fraction as described in Section 5.2.1.

5.4.2 Air Concentrations

Near the Pile

Average concentrations near the pile are shown in Figure 5-1 for a small (5 hectares or 12 acres), a medium (20 hectares or 49 acres), and a large (80 hectares or 196 acres) tailings pile. Our calculations show that the average concentration near the center of the pile and at the edge of the pile are relatively insensitive to the size of the pile. For the 20-hectare pile, Figure 5-1 also shows the results in the directions for which the concentration is maximum or minimum. The wind data (and therefore the dispersion) and the shape of the pile at actual sites would differ from the one used for these calculations. Although we have not performed site-specific calculations, we believe that the higher wind direction asymmetry at actual tailings sites would increase the maximum concentration at the edge of the tailings to about 4 pCi/L. This is the only calculation which uses dimensions different from those of the model pile described in Chapter 4.

Regional

Regional air concentrations for particulates and radon are shown in Table 5-1. These concentrations are based on the operational phase source terms given in Table 4-6. In Table 5-1 and subsequent tables, the column heading "average" refers to the arithmetic average over the sixteen directions for which concentrations are calculated. The heading "maximum" is the value for the direction of maximum risk (see

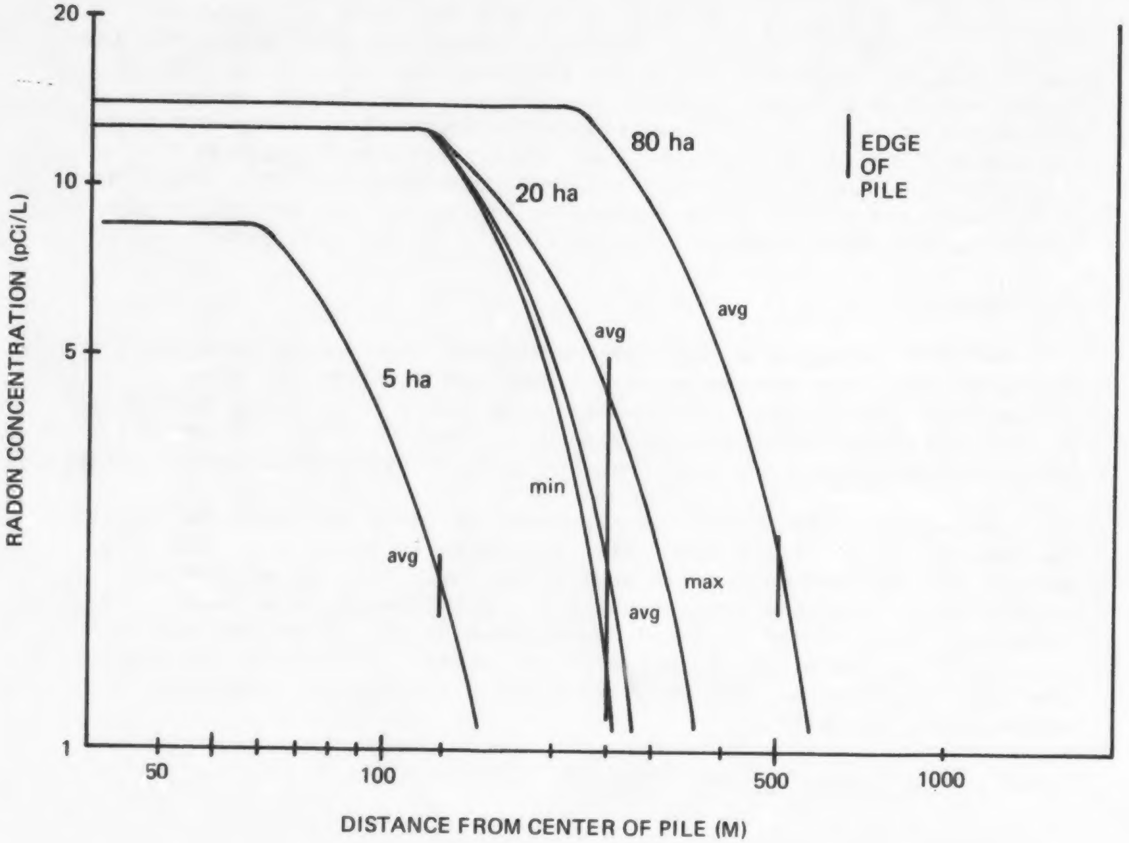

Figure 5-1. Radon Concentration Near the Tailings Pile. Radon Emission Rate is 280 pCi/m^{2}s.

Chapter 6) at that distance. The directions may differ since "risk" implies that an individual or population is present. In general, the direction of maximum concentration is the same as that of maximum risk; in those situations where it is not, the concentration for the direction of maximum risk does not differ in any practical sense from that in the direction of maximum concentration. Data in Table 5-1 and subsequent tables are presented to two significant figures to facilitate comparisons and not to indicate that environmental values can be calculated to that level of accuracy.

Table 5-2 shows population inhalation intakes of particulates and radon decay product exposures, calculated for a year's release during the operational period. The population distributions are shown in Tables 4-2 and 4-3. Note that the total intake/exposure values for the remote site are less than those for the rural one even though the remote site has a larger regional population. The larger nearby population of the rural site substantially increases the regional intakes and exposures for that site. Post-operational regional concentrations for particulates and radon are shown in Table 5-4. The entire tailings pile area is assumed to be dry in this period, so the emissions are 80/50 times the values for the operational phase.

National

National population exposures during the post-operational phase of the model mill are calculated in the same way as those for the operational phase. The radon source term, Table 4-6, during this phase is 7000 curies per year and the exposures shown in Table 5-5 are the total exposures for each year that the tailings pile continues to exist.

Annual national population exposures to radon emissions during the operational phase of the model mill are shown in Table 5-3. The total source term of 4400 curies per year (from Table 4-6) is attributed to each site in turn; the average value for all sites is also shown. These exposures assume an equilibrium fraction of 0.7 and exclude the population living within 50 miles of the sites. The values represent the total exposure to this population which results from each year's operation of the mill.

5.4.3 Ground Surface Concentrations

Operational

Table 5-6 shows the regional ground surface concentrations of radionuclides for the operational phase of the mill. These values are calculated after 15 years of operation. The "average" and "maximum" headings again refer to the average for all directions and the direction of maximum risk for all pathways.

Table 5-1. Regional Air Concentration (Ci/m^3) of Radionuclides by Distance and Particle Size (Operational Phase)

Distance (meters)	Average[a] 5 µm	Average[a] 35 µm	Maximum[b] 5 µm	Maximum[b] 35 µm
^{238}U, ^{234}U				
600	3.7E-16	6.5E-17	6.3E-16	1.5E-16
1000	1.1E-16	1.8E-17	2.2E-16	5.6E-17
2000	2.8E-17	3.5E-18	6.3E-17	1.3E-17
3000	1.2E-17	1.4E-18	2.9E-17	5.5E-18
4000	7.0E-18	6.9E-19	1.7E-17	2.8E-18
5000	4.6E-18	4.2E-19	1.1E-17	1.7E-18
10000	1.2E-18	7.5E-20	3.0E-18	3.1E-19
20000	3.2E-19	1.3E-20	8.8E-19	5.4E-20
^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po				
600	5.2E-15	9.3E-16	9.0E-15	2.2E-15
1000	1.6E-15	2.5E-16	3.1E-15	7.9E-16
2000	3.9E-16	5.0E-17	9.0E-16	1.9E-16
3000	1.8E-16	2.0E-17	4.2E-16	7.8E-17
4000	1.0E-16	9.8E-18	2.4E-16	4.0E-17
5000	6.6E-17	6.0E-18	1.6E-16	2.4E-17
10000	1.6E-17	1.1E-18	4.2E-17	4.4E-18
20000	4.6E-18	1.9E-19	1.3E-17	7.7E-19
^{222}Rn				
600	1.3E-09		2.0E-09	
1000	4.4E-10		7.7E-10	
2000	1.4E-10		2.7E-10	
3000	7.0E-11		1.4E-10	
4000	4.6E-11		9.5E-11	
5000	3.4E-11		6.9E-11	
10000	1.3E-11		2.6E-11	
20000	5.6E-12		1.1E-11	

(a)Value averaged over all directions.
(b)Value for direction of greatest risk.

Table 5-2. Regional Population Inhalation Intake and Exposure (per Operational Year)

Distance (km)	Number of Persons	Inhalation (person-pCi)				Radon Decay Product Exposure (person-WLy)
		^{238}U, ^{234}U		^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po		
		5 μm	35 μm	5 μm	35 μm	
		Remote Site[a]				
20	16	6.9	1.5	1.0E+02	2.2E+01	2.4E-02
20-40	4,572	4.9	7.5E-02	6.9E+01	1.1	1.5E-01
40-80	52,840	2.6E+01	7.3E-01	3.7E+02	1.0E+01	7.3E-01
Total	57,428	3.8E+01	2.3	5.4E+02	3.3E+01	8.9E-01
		Rural Site[a]				
20	2,273	2.0E+03	1.8E+02	2.8E+04	2.5E+03	7.0
20-40	5,314	1.2E+01	4.4E-01	1.8E+02	6.3	2.0E-01
40-80	14,235	2.8	3.6E-02	4.0E+01	5.1E-01	1.4E-01
Total	21,822	2.0E+03	1.8E+02	2.8E+04	2.6E+03	7.3

(a) See Chapter 4 for description of sites.

Table 5-3. National Population Exposures and Intakes (per Operational Year)

Release Site	Exposures		^{210}Pb Intakes	
	^{222}Rn (person-Ci-y/m^3)	Radon Decay Product (person-WLy)	Inhalation (person-Ci)	Ingestion (person-Ci)
New Mexico				
Grants	3.1E-07	2.2	7.7E-07	4.4E-06
Texas				
Falls City	4.8E-07	3.3	8.2E-07	2.7E-06
Washington				
Wellpinit	2.6E-07	1.9	7.9E-07	5.3E-06
Wyoming				
Casper	3.7E-07	2.6	9.4E-07	4.8E-06
Average	3.5E-07	2.5	8.3E-07	4.4E-06

Table 5-4. Regional Air Concentration (Ci/m^3) of Radionuclides by Distance and Particle Size(a) (Post-Operational Phase)

Distance (meters)	Average(a) 5 µm	Average(a) 35 µm	Maximum(b) 5 µm	Maximum(b) 35 µm
		^{238}U, ^{234}U		
600	5.9E-16	1.0E-16	1.0E-15	2.4E-16
1000	1.8E-16	2.8E-17	3.5E-16	8.9E-17
2000	4.4E-17	5.6E-18	1.0E-16	2.1E-17
3000	2.0E-17	2.2E-18	4.7E-17	8.7E-18
4000	1.1E-17	1.1E-18	2.7E-17	4.4E-18
5000	7.4E-18	6.7E-19	1.8E-17	2.7E-18
10000	1.8E-18	1.2E-19	4.8E-18	4.9E-19
20000	5.2E-19	2.1E-20	1.4E-18	8.6E-20
		^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po		
600	8.4E-15	1.5E-15	1.4E-14	3.5E-15
1000	2.6E-15	4.0E-16	5.0E-15	1.3E-15
2000	6.3E-16	8.0E-17	1.4E-15	3.0E-16
3000	2.8E-16	3.2E-17	6.7E-16	1.2E-16
4000	1.6E-16	1.6E-17	3.9E-16	6.3E-17
5000	1.1E-16	9.6E-18	2.6E-16	3.9E-17
10000	2.6E-17	1.7E-18	6.8E-17	7.0E-18
20000	7.3E-18	3.0E-19	2.0E-17	1.2E-18
		^{222}Rn		
600	2.0E-09		3.2E-09	
1000	7.1E-10		1.2E-09	
2000	2.2E-10		4.4E-10	
3000	1.1E-10		2.3E-10	
4000	7.4E-11		1.5E-10	
5000	5.4E-11		1.1E-10	
10000	2.0E-11		4.1E-11	
20000	9.0E-12		1.8E-11	

(a) Value averaged over all directions.
(b) Value for direction of greatest risk.

Table 5-5. National Population Exposures and Intakes Per Year (Post-Operational Phase)

Release Site	Exposures		^{210}Pb Intakes	
	^{222}Rn (person-Ci-y/m^3)	Radon Decay Products (person-WLy)	Inhalation (person-Ci)	Ingestion (person-Ci)
New Mexico				
Grants	4.9E-07	3.5	1.2E-06	7.0E-06
Texas				
Falls City	7.6E-07	5.3	1.3E-06	6.4E-06
Washington				
Wellpinit	4.2E-07	3.0	1.3E-06	8.4E-06
Wyoming				
Casper	5.8E-07	4.1	1.5E-06	7.7E-06
Average	5.7E-07	4.0	1.3E-06	7.0E-06

Table 5-6. Regional Ground Surface Concentrations (Ci/m^2) for Radionuclides[(a)] (Operational Phase)

Distance (meters)	^{238}U, ^{234}U		^{230}Th, ^{226}Ra		^{210}Pb, ^{210}Po	
	Average	Maximum	Average	Maximum	Average	Maximum
600	3.9E-09	8.1E-09	5.5E-08	1.2E-07	5.3E-08	1.1E-07
1000	1.1E-09	2.9E-09	1.6E-08	4.2E-08	1.5E-08	4.0E-08
2000	2.4E-10	7.4E-10	3.5E-09	1.0E.08	3.3E-09	1.0E-08
3000	1.0E-10	3.2E-10	1.5E-09	4.6E-09	1.4E-09	4.4E-09
4000	5.5E-11	1.7E-10	7.8E-10	2.5E-09	7.5E-10	2.4E-09
5000	3.5E-11	1.1E-10	5.0E-10	1.6E-09	4.8E-10	1.5E-09
10000	7.7E-12	2.4E-11	1.1E-10	3.5E-10	1.1E-10	3.3E-10
20000	1.9E-12	5.9E-12	2.7E-11	8.4E-11	2.6E-11	8.1E-11

(a) Average: value averaged over all directions.
Maximum: value for direction of greatest risk.

Table 5-7. Regional Population Ground Surface Exposure (person-Ci/m^2) for Radionuclides (per Operational Year)

Distance (km)	Number of Persons	^{238}U, ^{234}U	^{230}Th, ^{226}Ra	^{210}Pb, ^{210}Po
		Remote Site[a]		
20	16	3.3E-08	4.7E-07	4.2E-07
20-40	4,572	9.9E-09	1.4E-07	1.2E-07
40-80	52,840	5.9E-08	8.4E-07	7.4E-07
Total	57,428	1.0E-07	1.5E-06	1.3E-06
		Rural Site[a]		
20	2,273	5.8E-06	8.3E-05	7.3E-05
20-40	5,314	2.9E-08	4.1E-07	3.6E-07
40-80	14,235	5.9E-09	8.4E-08	7.5E-08
Total	21,822	5.8E-06	8.3E-05	7.3E-05

(a) See Chapter 4 for description of sites.

Table 5-8. Regional Ground Surface Concentrations (Ci/m^2) for Radionuclides by Distance[a] (Post-Operational Phase)

Distance (meters)	^{238}U, ^{234}U Average	Maximum	^{230}Th, ^{226}Ra Average	Maximum	^{210}Pb, ^{210}Po Average	Maximum
600	2.1E-08	4.3E-08	2.9E-07	6.2E-07	2.6E-07	5.5E-07
1000	5.9E-09	1.6E-08	8.4E-08	2.2E-07	7.4E-08	2.0E-07
2000	1.3E-09	3.9E-09	1.8E-08	5.6E-08	1.6E-08	4.9E-08
3000	5.5E-10	1.7E-09	7.8E-09	2.4E-08	6.9E-09	2.2E-08
4000	2.9E-10	9.2E-10	4.2E-09	1.3E-08	3.7E-09	1.2E-08
5000	1.9E-10	5.9E-10	2.7E-09	8.4E-09	2.4E-09	7.4E-09
10000	4.1E-11	1.3E-10	5.9E-10	1.8E-09	5.2E-10	1.6E-09
20000	1.0E-11	3.2E-11	1.5E-10	4.5E-10	1.4E-10	4.4E-10

(a) Average: value averaged over all directions.
Maximum: value for direction of greatest risk.

Regional population surface exposures for the operational phase corresponding to these concentrations are shown in Table 5-7. These values give the total exposure to the population for each year's operation of the mill.

The national population dose resulting from deposition of radon decay products, primarily the long-lived lead-210, is dominated by the ingestion pathway. For this reason, separate ground surface exposures are not given here. Intakes due to ingestion are discussed in Section 5.4.4.

Post Operational

Post-operational regional ground surface concentrations are given in Table 5-8. These representative values are calculated for the end of a 100-year release period.

Since only the magnitude of the source term is different, post-operational surface exposures are not listed separately. They may be obtained by multiplying the values in Table 5-7 by factor 1.6.

Separate national ground exposures are not shown, since they are not significant compared to ingestion doses, which are given below.

5.4.4 Dietary Intake

Food consumption fractions for the regional population are shown in Table 5-9. We have assumed that the mill is sited in a region of low agricultural productivity and that area residents produce the same amount of their own food supply as urban residents.

Table 5-9. Regional Food Utilization Factors for An Individual

Type of Food	Home Produced (Percent)	Total Annual Consumption
Leafy vegetables	7.6	18 kg
Other produce	7.6	176 kg
Milk	0.0	112 L
Meat	0.8	85 kg

Annual ingestion intakes for an individual residing in the region are given in Table 5-10 for the operational phase and in Table 5-11 for the post-operational phase. Annual regional population ingestion values for the operational phase are given in Table 5-12. Since the only difference is in the source term, values for the post-operational phase are a factor of 1.6 larger than those in Table 5-12.

Annual national population exposures due to the ingestion of long-lived radon decay products are dominated by lead-210. Dose and risk calculations take account of the lead decay products as they build up within the body following lead-210 intake. Table 5-3 gives the annual population exposure resulting from dietary intake of lead-210 during the operational phase of the model mill. Post-operational exposures are shown in Table 5-5.

5.4.5 Water Concentrations

In general, meaningful modeling of water pathways can be done only on a site-specific basis, since any model depends strongly on the hydrological and geological characteristics of the area. NRC (NRC80) has performed a detailed analysis for the model mill based on a set of assumed parameters. However, the environmental impact of a given tailings pile depends on so many factors, i.e., wind erosion, floods, slides into nearby streams, seepage through the pile, runoff of rainwater, etc., that each must be evaluated on an ad hoc basis.

Surface Water

During operation of the mill, the pathways noted in Section 5.3 could cause the transfer of contaminants to surface waters. However, based on the rainfall in the model mill region, the quantities of material washed or leached into flowing surface waters could be so dispersed and rapidly diluted that it is unlikely that surface water would pose a significant health problem. Since the moisture content of the tailings is reduced after mill operations cease, the potential for surface water contamination is even less.

Under the Clean Water Act, effluent guidelines are already in effect for uranium mills. In addition, EPA has New Source Performance Standards for new uranium mills that would eliminate the discharge of process waste water. In view of this comprehensive regulatory program for surface water discharges from the uranium milling industry, surface water contamination is not addressed in this analysis.

Groundwater

The modeling of groundwater contamination by tailings piles depends strongly on the chemical and physical properties of the underground environment. The NRC model predicts that, in spite of the initial presence of radioactive materials in the seepage, no

Table 5-10. Regional Individual Annual Ingestion (pCi) for Radionuclides(a)
(Operational Phase)

Distance (meters)	^{238}U, ^{234}U Average	Maximum	^{230}Th Average	Maximum	^{226}Ra Average	Maximum	^{210}Pb Average	Maximum	^{210}Po Average	Maximmum
600	3.3E+01	6.9E+01	4.6E+02	9.6E+02	7.3E+02	1.5E+03	4.7E+03	1.0E+03	4.1E+02	8.6E+02
1000	9.4	2.5E+01	1.3E+02	3.4E+02	2.1E+02	5.5E+02	1.3E+02	3.6E+02	1.2E+02	3.1E+02
2000	2.1	6.3	2.8E+01	8.6E+01	4.6E+01	1.4E+02	3.0E+01	9.0E+01	2.6E+01	7.8E+01
3000	8.7E-01	2.7	1.2E+01	3.8E+01	1.9E+01	6.0E+01	1.3E+01	3.9E+01	1.1E+01	3.4E+01
4000	4.7E-01	1.5	6.4	2.0E+01	1.0E+01	3.2E+01	6.7	2.1E+01	5.8	1.8E+01
5000	3.0E-01	9.4E-01	4.1	1.3E+01	6.6	2.1E+01	4.3	1.3E+01	3.7	1.2E+01
10000	6.6E-02	2.1E-01	9.1E-01	2.8	1.4	4.5	9.4E-01	3.0	8.2E-01	2.6
20000	1.6E-02	5.0E-02	2.3E-01	6.9E-01	3.6E-01	1.1	2.4E-01	7.2E-01	2.0E-01	6.3E-01

(a)Average: value averaged over all directions.
Maximum: value for direction of greatest risk.

Table 5-11. Regional Individual Annual Ingestion (pCi) for Radionuclides (Post-Operational Phase)(a)

Distance (meters)	^{238}U, ^{234}U		^{230}Th		^{226}Ra		^{210}Pb		^{210}Po	
	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximmum
600	5.7E+01	1.2E+02	7.3E+02	1.5E+03	2.2E+03	4.5E+03	8.2E+02	1.7E+03	6.6E+02	1.4E+03
1000	1.6E+01	4.3E+01	2.1E+02	5.5E+02	6.1E+02	1.6E+03	2.3E+02	6.2E+02	1.9E+02	5.0E+02
2000	3.6	1.1E+01	4.6E+01	1.4E+02	1.4E+02	4.1E+02	5.1E+01	1.6E+02	4.1E+01	1.3E+02
3000	1.5	4.7	1.9E+01	6.1E+01	5.7E+01	1.8E+02	2.2E+01	6.8E+01	1.7E+01	5.5E+01
4000	8.0E-01	2.5	1.0E+01	3.3E+01	3.0E+01	9.6E+01	1.2E+01	3.6E+01	9.3	2.9E+01
5000	5.1E-01	1.6	6.6	2.1E+01	2.0E+01	6.2E+01	7.4	2.3E+01	6.0	1.9E+01
10000	1.1E-01	3.6E-01	1.5	4.6	4.3	1.4E+01	1.6	5.1	1.3	4.1
20000	2.8E-02	8.7E-02	3.6E-01	1.1	1.1	3.3	4.1E-01	1.2	3.3E-01	1.0

(a)Average: value averaged over all directions.
Maximum: value for direction of greatest risk.

radioactive contamination of groundwater would be expected during or after mill operation. Based on their parameters, many of the contaminants present in the acidic tailings pond water would precipitate out or undergo ion exchange and be removed by soil from the tailings seepage water. Potential contamination, as indicated by this model, would be limited to toxic materials having relatively high mobility. The health aspects of these materials are discussed in Chapter 6.

Since control of groundwater pollution is already required for conformance with existing water protection regulations, we have not performed a detailed analysis for this pathway.

Table 5-12. Regional Population Ingestion (person-pCi) for Radionuclides (per Operational Year)

Distance (km)	Number of Persons	^{238}U, ^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po
			Remote Site(a)			
20	16	1.4	1.8E+01	5.6E+01	2.3E+01	2.7E+01
20-40	4,572	4.1E+02	5.3E+03	1.6E+04	6.5E+03	7.8E+03
40-80	52,840	4.7E+03	6.0E+04	1.8E+05	7.5E+04	9.0E+04
Total	57,428	5.1E+03	6.5E+04	2.0E+05	8.2E+04	9.8E+04
			Rural Site(a)			
20	2,273	3.0E+02	3.9E+03	1.2E+04	4.7E+03	5.0E+03
20-40	5,314	7.1E+02	9.1E+03	2.8E+04	1.1E+04	1.2E+04
40-80	14,235	1.9E+03	2.4E+04	6.9E+04	2.9E+04	3.1E+04
Total	21,822	2.9E+03	3.7E+04	1.1E+05	4.5E+04	4.8E+04

(a)See Chapter 4 for description of sites.

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Chapter 6: HEALTH IMPACT OF TAILINGS BASED ON MODEL TAILINGS PILES

In this chapter we consider the health impact of material coming from the model pile. When feasible, projections, based on these results, for the total impact of the industry are developed in Chapter 10. Data on the concentrations of radioisotopes for individuals or populations at various distances from the model pile, taken from Chapter 5, were combined with the risk coefficients described in Appendix C to estimate the risks to individuals and populations living around the model pile. Potential effects on local, regional, and national populations are estimated.

6.1 Introduction

Among metallic ore wastes, uranium tailings piles are unusual because of the amount of radioactivity they contain. Radioactivity probably constitutes the principal source of hazard to health from these wastes, although nonradioactive toxic chemicals, such as arsenic, lead, selenium, mercury, sulphates, and nitrates are usually present. Milling of uranium ore removes about 90 percent of the uranium in the ore. The remainder, along with most other radioactive materials and toxic chemicals, is discarded in the liquid and solid wastes discharged to tailings piles.

The principal isotope of uranium, uranium-238, decays over billions of years to become lead, a stable nonradioactive element. This lengthy decay process involves a series of intermediate radioactive decay products, such as thorium-230, radium-226, and radon-222. The decay of uranium since the ore was formed millions of years ago has built up an inventory of these decay products, which are present in uranium mill tailings in various concentrations.

The dominant hazard from tailings is due to the radioactive decay products of uranium-238, particularly radium-226 and its short half-life decay products. Each gram of natural uranium ore contains about 490 pCi each of uranium-238 and uranium-234 and additionally about 23 pCi of uranium-235 and 2 pCi of thorium-232. Because they occur in relatively small proportions and/or pose much less risk to health, uranium-235 and thorium-232 and their radioactive decay products may usually be ignored in evaluating the hazard of uranium tailings.

Uranium tailings emit three kinds of radiation: alpha particles, beta particles, and gamma rays. All are forms of ionizing radiation, which breaks up molecules into electrically charged fragments called ions. In biological tissues, this ionization can produce harmful cellular changes. At the low radiation levels usually encountered in the environment, we expect the effects of such changes to be difficult to detect. Studies show, however, that people exposed to radiation have a greater chance of developing cancer. If the ovaries or testes are exposed, the health or development of future generations of children may also be impaired due to genetic damage.

One cannot predict with precision the increased chance of cancer or genetic damage after exposure to radiation. We have based our risk estimates on studies of persons exposed at doses higher than those usually resulting from tailings and the assumption that at lower doses the effects will be proportionally less. This assumption may overestimate or underestimate the actual risk, but it is the best that can be done at present (EPA76).

Alpha, beta, and gamma radiations from mill tailings can cause cancer or genetic damage. However, the major threat comes from breathing air containing radon decay products with short half-lives--polonium-218, for example--and exposing the lungs and other internal organs to the alpha radiation these decay products emit. In addition, people may be directly exposed to gamma rays from radioactive material in the tailings pile, and radioactive tailings particles may be transported into the body by breathing or ingestion.

The body's internal organs would still be exposed to radiation from radionuclides even if uranium tailings piles suddenly disappeared, because radon, radium, uranium, thorium, and other radioactive elements occur naturally in the air, rock, and soil. One picocurie of radium per gram of soil is a typical concentration; outdoor air contains a few tenths of a picocurie of radon per liter (UN77). Normal eating and breathing introduce these and other radioactive materials into the body, increasing the potential for cancer and genetic changes. This discussion, therefore, also compares the health risks from tailings to those from normal exposure--not to justify the tailings risk, but to provide a realistic context for comparison.

Tailings also contain toxic elements that could eventually be inhaled or ingested by man and animals or absorbed by plants. Windblown tailings inhaled by man or animals are unlikely to cause any toxicity problems because the mass of inhaled material is so small. However, the toxic elements in windblown tailings could be absorbed by plants growing near a pile and could be a potential pathway leading to chronic toxicity diseases in men or animals eating those plants. Moreover, toxic elements from tailings could leach or seep into water supplies used for irrigation or drinking. Finally, windblown tailings and radon decay products could be deposited directly onto some foods, such as lettuce and spinach.

It is important to distinguish between acute and chronic toxicity. Acute toxicity (or poisoning) occurs when enough of the toxic element is consumed to interfere with a vital body or organ function. The severity of the poisoning is usually proportional to the amount of the toxic element consumed, and in extreme cases death or permanent injury will occur. Chronic toxicity is more insidious. It occurs when small amounts of a toxic element are consumed over a prolonged period of time. A small fraction of each intake may be deposited in tissues or organs. Toxic symptoms appear when the cumulative deposit exceeds a critical level. Alternatively, each intake of a toxic element may cause a small increment of organ damage. Symptoms of toxicity become apparent when this damage accumulates to a critical extent. Symptoms of chronic toxicity may be reversible if consumption of the toxic element is stopped, or they may be irreversible, progressive, or both.

In the case of tailings, acute toxicity would be a problem only if standing water adjacent to or on a pile is consumed. Chronic toxicity is more likely and is therefore examined in later discussions.

6.1.1 Radon and its Immediate Decay Products

Since the milling and extraction processes have removed most of the uranium from the ore, the longevity of the remaining radioactive members of the uranium series is determined by the presence of thorium-230, which has a 77,000-year half-life. The thorium-230 decay product, radium-226, has a 1,600-year half-life. Both thorium and radium are relatively insoluble and immobile in their usual chemical forms. However, the decay product of radium-226 is radon-222, an inert radioactive gas, that readily diffuses through interstitial spaces to the surface of the tailings pile where it becomes airborne. The half-life of radon-222 is 3.8 days, so some radon atoms can travel thousands of miles through the atmosphere before they decay.

As shown in Figure 3-1, the radon decay process involves seven principal decay products before ending with nonradioactive lead. The four short half-life radioactive decay products immediately following radon are the most important sources of cancer risk. These decay, for the most part, within less than an hour. Members of the decay chain with relatively long half-lives (beginning with lead-210, which has a 22-year half-life) are more likely to be ingested than breathed and represent much smaller risks.

The principal short half-life products of radon are polonium-218, lead-214, bismuth-214, and polonium-214. Polonium-218, the first decay product, has a half-life of just over 3 minutes. This is long enough for most of the electrically charged polonium atoms to attach themselves to microscopic airborne dust particles that are typically less than a millionth of a meter across. When breathed, these small particles have a good chance of sticking to the moist epithelial lining of the bronchial.

Most inhaled particles are eventually cleared from the bronchi by mucus, but not quickly enough to keep the bronchial epithelium from being exposed to alpha radiation from polonium-218 and polonium-214. This highly ionizing radiation passes through and delivers radiation doses to several types of lung cells. The exact doses delivered to cells that eventually become cancerous cannot be characterized adequately. Also, we do not have detailed knowledge of the deposition pattern of the radioactive particles in the lung and the distances from them to cells that are susceptible. Further, there is some disagreement about the types of bronchial cells where cancer originates. Therefore, we have based our estimates of lung cancer risk on the amount of inhaled radon decay products to which people are exposed, rather than on the dose absorbed by the lung.

6.2 Estimated Effects on Health Due to Radioactive Releases from the Model Tailings Pile

Risk factors from Tables C-3 to C-10 (see Appendix C) were used in the DARTAB computer code to determine individual and population lifetime risks for continuous exposure to emissions from the model tailings pile. The calculated health impact on individuals and populations is shown in Tables 6-1 through 6-6. The risk averages given are population averages over the indicated sector. As shown in these tables, about 99 percent of the inhalation risk is due to radon and its daughters.

Values in these tables are shown to two significant figures solely to facilitate comparisons and additional calculations; these projections have overall uncertainties of at least a factor of 2 or 3. The individual health risks are for a lifelong exposure to the environmental concentrations discussed in Chapter 5. A shorter period of exposure may be assessed by assuming that the risk due to that exposure or intake had been spread over the individual's lifetime. For example, the risk from a 15-year exposure would be approximated as 15/70.76 times the lifetime (70.76 years is the expected lifespan of an individual in the RADRISK cohort). The population health effect values are the number of cancer deaths per year calculated at equilibrium for a stationary population living at the calculated environmental concentration levels. These values are equivalent to the number of health effects committed per year of operation. (The age distribution of the stationary population is that for the U.S. population in 1970, a constant birth rate, and no external migration.)

6.2.1 Effects of Radioactive Particulate Releases from the Model Tailings Pile

Individuals and Regional Populations

Windblown tailings from the model tailings pile may be inhaled by persons in the vicinity of the pile. They may also be deposited on soil or vegetation, be transferred to edible plants and ingested by members of the population around the pile. The contribution of these

Table 6-1. Regional Individual Lifetime Risk of Fatal Cancer (Operational Phase)

Distance (meters)	Ingestion		Particulates--Inhalation		Ground Surface Exposure		Radon Decay Products		Total	
	Average[a]	Maximum[b]	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
600	1.1E-05	2.4E-05	6.2E-05	1.1E-04	7.8E-05	1.7E-04	1.5E-02	2.4E-02	1.5E-02	2.4E-02
1000	3.2E-06	8.5E-06	1.9E-05	3.8E-05	2.2E-05	5.9E-05	5.3E-03	9.2E-03	5.3E-03	9.3E-03
2000	7.0E-07	2.1E-06	4.6E-06	1.1E-05	4.9E-06	1.5E-05	1.6E-03	3.2E-03	1.6E-03	3.2E-03
3000	3.0E-07	9.3E-07	2.0E-06	5.0E-06	2.1E-06	6.5E-06	8.3E-04	1.7E-03	8.3E-04	1.7E-03
4000	1.6E-07	5.0E-07	1.1E-06	2.8E-06	1.1E-06	3.5E-06	5.5E-04	1.1E-03	5.5E-04	1.1E-03
5000	1.0E-07	3.2E-07	7.6E-07	1.9E-06	7.1E-07	2.2E-06	4.0E-04	8.2E-04	4.0E-04	8.2E-04
10000	2.2E-08	7.0E-08	1.9E-07	4.9E-07	1.6E-07	4.9E-07	1.5E-04	3.1E-04	1.5E-04	3.1E-04
20000	5.6E-09	1.7E-08	5.2E-08	1.4E-07	3.9E-08	1.2E-07	6.6E-05	1.3E-04	6.6E-05	1.3E-04

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[a] Average population weighted dose over all wind directions.

[b] Dose to individual in direction of maximum exposure.

Table 6-2. Regional Individual Lifetime Risk of Fatal Cancer
(Post-Operational Phase)

Distance (meters)	Ingestion		Particulates--Inhalation		Ground Surface Exposure		Radon Decay Products		Total	
	Average[a]	Maximum[b]	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
600	2.5E-05	5.5E-05	9.9E-05	1.7E-04	4.1E-04	9.0E-04	2.4E-02	3.8E-02	2.5E-02	3.9E-02
1000	7.2E-06	1.9E-05	3.0E-05	6.1E-05	1.2E-04	3.1E-04	8.4E-03	1.5E-02	8.6E-03	1.5E-02
2000	1.6E-06	4.8E-06	7.3E-06	1.7E-05	2.6E-05	7.9E-05	2.6E-03	5.2E-03	2.6E-03	5.3E-03
3000	6.7E-07	2.1E-06	3.2E-06	7.9E-06	1.1E-05	3.4E-05	1.3E-03	2.7E-03	1.3E-03	2.7E-03
4000	3.6E-07	1.1E-06	1.8E-06	4.5E-06	5.8E-06	1.8E-05	8.8E-04	1.8E-03	8.9E-04	1.8E-03
5000	2.3E-07	7.2E-07	1.2E-06	3.0E-06	3.7E-06	1.2E-05	6.4E-04	1.3E-03	6.5E-04	1.3E-03
10000	5.0E-08	1.6E-07	3.0E-07	7.8E-07	8.2E-07	2.6E-06	2.4E-04	4.9E-04	2.4E-04	4.9E-04
20000	1.3E-08	3.9E-08	8.2E-08	2.3E-07	2.1E-07	6.3E-07	1.1E-04	2.1E-04	1.1E-04	2.1E-04

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[a] Average population weighted dose over all wind directions.

[b] Dose to individual in direction of maximum exposure.

Table 6-3. Number of Fatal Cancers per Operational Year for the Regional Population

Distance (km)	Number of Persons	Radioactive Particulates				Radon Decay Products	Total
		Ingestion	Inhalation	Ground Surface	Subtotal		
				Remote Site(a)			
20	16	1.0E-08	2.0E-06	9.4E-06	1.1E-05	5.7E-04	5.8E-04
20-40	4,572	2.9E-06	1.3E-06	2.8E-06	7.0E-06	3.5E-03	3.5E-03
40-80	52,840	3.4E-05	6.9E-06	1.7E-05	5.8E-05	1.7E-02	1.7E-02
Total	57,428	3.7E-05	1.0E-05	2.9E-05	7.6E-05	2.1E-02	2.1E-02
				Rural Site(a)			
20	2,273	2.1E-06	5.4E-04	1.6E-03	2.1E-03	1.7E-01	1.7E-01
20-40	5,314	4.9E-06	3.3E-06	8.3E-06	1.7E-05	4.8E-03	4.8E-03
40-80	14,235	1.3E-05	7.5E-07	1.7E-06	1.5E-05	3.3E-03	3.3E-03
Total	21,822	2.0E-05	5.5E-04	1.7E-03	2.3E-03	1.8E-01	1.8E-01

(a) See Chapter 4 for description of sites.

Table 6-4. Number of Fatal Cancers per Post-Operational Year for the Regional Population

Distance (km)	Number of Persons	Radioactive Particulates				Radon Decay Products	Total
		Ingestion	Inhalation	Ground Surface	Subtotal		
				Remote Site(a)			
20	16	1.6E-08	3.2E-06	1.5E-05	1.8E-05	9.1E-04	9.3E-04
20-40	4,572	4.6E-06	2.1E-06	4.5E-06	1.1E-05	5.6E-03	5.6E-03
40-80	52,840	5.4E-05	1.1E-05	2.7E-05	9.2E-05	2.7E-02	2.7E-02
Total	57,428	5.9E-05	1.6E-05	4.6E-05	1.2E-04	3.4E-02	3.4E-02
				Rural Site(a)			
20	2,273	3.4E-06	8.6E-04	2.6E-03	3.5E-03	2.7E-01	2.7E-01
20-40	5,314	7.8E-06	5.3E-06	1.3E-05	2.6E-05	7.7E-03	7.7E-01
40-80	14,235	2.1E-05	1.2E-06	2.7E-06	2.5E-05	5.3E-03	5.3E-03
Total	21,822	3.2E-05	8.8E-04	2.7E-03	3.6E-03	2.9E-01	2.9E-01

(a) See Chapter 4 for description of sites.

Table 6-5. U.S. Collective Risks due to ^{222}Rn Release per Operational Year (Fatal Cancers)

Release Site	^{210}Pb Intake			Radon Decay Product Exposure
	Inhalation	Ingestion	Total	
New Mexico				
Grants	1.0E-04	2.1E-04	3.2E-04	5.2E-02
Texas				
Falls City	1.1E-04	1.3E-04	2.4E-04	8.0E-02
Washington				
Wellpinit	1.1E-04	2.5E-04	3.6E-04	4.4E-02
Wyoming				
Casper	1.3E-04	2.3E-04	3.5E-04	6.1E-02
Average	1.1E-04	2.1E-04	3.2E-04	5.9E-02

Table 6-6. U.S. Collective Risks due to ^{222}Rn Release per Post-Operational Year (Fatal Cancers)

Release Site	^{210}Pb Intake			Radon Decay Product Exposure
	Inhalation	Ingestion	Total	
New Mexico				
Grants	1.6E-04	3.3E-04	5.0E-04	8.2E-02
Texas				
Falls City	1.8E-04	2.1E-04	3.8E-04	1.3E-01
Washington				
Wellpinit	1.7E-04	4.0E-04	5.7E-04	7.1E-02
Wyoming				
Casper	2.0E-04	3.7E-04	5.7E-04	9.8E-02
Average	1.8E-04	3.3E-04	5.1E-04	9.5E-02

two pathways is included in the risk estimates listed in Tables 6-1 to 6-4. The period for greatest risk from windblown particulates is during the post-operational phase of the mill after the tailings pile has been allowed to dry (Tables 6-2, 6-4).

The risk (expectation of developing a fatal cancer) to an individual for a lifelong exposure is shown in Tables 6-1 and 6-2 as a function of distance from the center of the pile. Risks from all pathways of exposure are listed for the maximum exposed individual at each distance. Depending on whether the local population density is high or low, e.g., a rural site versus a remote site, the expected number of fatal cancers in the regional population may vary by orders of magnitude as shown in Tables 6-3 and 6-4.

6.2.2 Effects of Radon Emissions from Tailings Piles

Individuals and Regional Populations

Detailed information is needed to determine the exposure due to radon decay products in a population. An accurate calculation of the collective exposure from a particular pile would require, in addition to the number of people exposed, the site and ventilation characteristics of each person's residence and work place, the length of time a person spends at each place, and the average annual distribution of wind speed and direction.

We have estimated local and regional exposure at the model site using the methods to estimate exposures described in Section 5.4. Although we have fixed our population at 1970 values, subsequent changes are almost certain. We have not attempted to update our population estimates because the data available reflect changes at large levels of aggregation (e.g., a State) which do not give information about the increases and decreases which have taken place at a more local level.

The excess risk to people due to exposure to radon decay products depends on their distance from the pile. Tables 6-1 and 6-2 list estimated excess risks to individuals for lifetime residency, as a function of distance from a model pile during operational and post-operational phases of the pile, respectively. The decay product concentrations are based on a dispersion factor that depends on the area of the pile out to a distance of several pile diameters. Beyond that distance the theoretical pile can be considered as a point source for the purpose of estimating concentration levels. The estimates for this pile are based upon the relative risk model and assume a stationary population.

The estimated risk of lung cancer from naturally-occurring radon decay products found in homes that are not near mill tailings or any other specifically identified radon source is 0.004 to 4 chances in 1,000 (EPA82). National data on radon decay products in homes (EPA82) are scanty and vary widely among individual houses. These estimates are based on the assumption that the average radon decay product concentration is 0.004 WL in homes and that they are occupied 75 percent of the time. This assumed average level of radon decay products is based on recent data on 21 houses in New York and New Jersey (Ge78) and on 26 houses in Florida (EPA79) and is consistent with data obtained in other countries (UN77). For comparison, these risks are about 10 percent of the expected lifetime risk of lung cancer death from all causes (0.029) in a stationary population having 1970 U.S. lung cancer mortality rates.

Effects on the U.S. Population

Radon emissions from a tailings pile may affect the health of populations beyond 80 kilometers from tailings piles. The aggregate effect on persons living more than 80 kilometers from the pile is summarized in Tables 6-5 and 6-6. These results are estimates of the total risk committed over 100 years to an exposed population of 200 million persons. Although the U.S. population increase has not been uniform, an increased risk on the order of 20 percent should provide a rough estimate of the risk to the current population.

Effects from Long-Lived Radioactive Decay Products of Radon

The long-lived decay products of radon, beginning with lead-210 (see Figure 3-1), are also potential hazards. A quantitative estimate of the impact of eating and breathing long-lived decay products from the model pile cannot be established without site-specific information--on food sources (Tr79), for example. The only detailed study available was prepared by Oak Ridge National Laboratory (Tr79) for the four sites listed in Chapter 5. We used these results in an input to our risk models to compare their importance to that of the short-lived decay products of radon. These comparisons are shown in Tables 6-5 and 6-6. These results should not be taken as quantitative estimates of the actual risk at specific inactive sites.

The four sources of exposure in this analysis are shown in Tables 6-1 to 6-4. The largest risk is from breathing short-lived radon decay products; the risk is 100 to 1000 times greater than the next highest risk, for both individuals and for the regional population. Persons living more than 80 kilometers from a model pile are less exposed, and their risk would be considerably below that indicated in Tables 6-1 to 6-4. But again, the risk from breathing short-lived radon decay products is about 100 times greater than from other pathways (Tables 6-5 and 6-6). We conclude that the risks from these pathways can be ignored compared to that from breathing short-lived radon decay products.

6.2.3 Effects of Gamma Radiation Emissions from Tailings Piles and Windblown Tailings

Gamma radiation exposure of individuals depends on how close to the edge of a pile people live or work and how tailings from the pile are distributed by the wind. The collective gamma radiation dose depends on both the number of people exposed and their doses. Potential individual doses can be approximated from available data, but accurate estimates cannot be made without a variety of detailed information, such as where people live and work and the amount of shielding provided by buildings.

Gamma radiation from tailings exposes the entire body so that all organs are at risk. The estimated frequency of fatal cancer and serious genetic effects due to exposure of 1 mrad/y are listed in Tables C-1 and C-2 in Appendix C. People who live or work near tailings piles will incur additonal risk from long-term exposures in proportion to the excess of their average lifetime annual dose rate above the normal background rate (approximately 100 mrem per year). The estimated contribution of gamma radiation emissions to individuals and populations in the vicinity of the model tailings pile is shown in Tables 6-1 to 6-4 in the column headed "Ground Surface."

6.3 Effects from Misuse of Tailings

When tailings are used in building construction, there can be serious risks to the health of those who live in such buildings. The Grand Junction experience is an example of what can happen when this kind of misuse occurs. There, about 700 buildings are contaminated with enough tailings to increase average indoor radon decay product levels by at least 0.01 WL; a few houses have levels higher than 0.5 WL. If it is assumed that the useful lifetime of these buildings is 70 years, we estimate about an additional 70-150 lung cancers would occur if remedial measures were not taken.

The estimated risks to individuals exposed to these high levels of radon decay products are very large. For persons living in a house with a concentration of 0.1 WL, the potential excess lifetime risk of lung cancer is 0.5 to 1 chance in 10.

Other misuses of tailings, e.g., tailings used in gardens or underneath detached buildings, can cause effects on health, but these cannot be estimated easily. The risks depend on the particular way in which the tailings are used, and effects on health may be due to gamma radiation, ingestion of radionuclides through food chains, or inhalation.

6.4 Estimated Effects on Health Due to Toxic Releases from the Model Tailings Pile

Toxic materials have been considered in this EIS if they are in substantially greater concentration in tailings than in native rocks or soils or in a relatively mobile form (as either anions or cations). We have included materials that are harmful to livestock and plants as well as those potentially affecting humans directly. Evaluating the potential risks from nonradioactive toxic substances in tailings requires different methods from those used for radioactive substances.(1) With nonradioactive toxic materials the type of effect varies with the material; the severity of the effect--but not its probability of occurring--increases with the dose. Moreover, because the body can detoxify some materials or repair the effects of some small doses, often no toxic effects occur below a threshold dose.

We cannot construct a numerical risk assessment for nonradioactive toxic substances because we do not have enough information. We can, however, qualitatively describe risks of toxic substances in terms of their likelihood of reaching people (or animals, or agricultural products), concentrations at which they may be harmful, and their toxic effects.

No acute effects--death in minutes or hours--could occur except by drinking liquid directly from a tailings pond. Severe sickness, or death within days to weeks, from the use of highly contaminated water is possible, but very unlikely.

Chronic toxicity from the continuous consumption of contaminants at low concentrations could be a problem. Toxic substances can accumulate slowly in tissues, causing symptoms only after some minimum amount has accumulated. Such symptoms of chronic toxity develop slowly, over months or years.

In Table 4-5 we listed many chemical elements and ions that have been found in tailings piles. Many of these occur in tailings in only slightly higher concentrations than in background soils, and they also have low toxicity when taken orally (Ve78). The following elements are in this category: lanthanides, including cerium, europium, lanthanum, and terbium; silicates; and zirconium, scandium, boron, gallium, and aluminum. Some other elements may be in elevated concentrations in tailings, but they, too, are not very toxic. These include copper, manganese, magnesium, cobalt, iron, vanadium, zinc, potassium, chloride, and sulfate. Some elements and ions at concentrations well below levels toxic to humans and animals will cause water to have an objectionable taste and color. Examples are iron, copper, manganese, chloride, and sulfate.

Other substances are both present in tailings and are regulated under the National Interim Primary Drinking Water Regulations (NIPDWR). Listing in the NIPDWR is an indication of a significant need to limit direct human consumption of these substances. The NIPDWR cover the following elements: arsenic, barium, cadmium, chromium, lead, mercury, nitrate, selenium, and silver. The toxicologies of these substances are discussed in Appendix C. Molybdenum is both toxic and present in tailings in elevated concentrations; its toxicity is also discussed in Appendix C. Appendix C also discusses both the chemical and radiological toxic effects of ingesting radium, thorium, and uranium. Tailings are not known to be significant sources of other toxic materials regulated under the NIPDWR, such as organic substances, microbiological organisms, and man-made radioactivity.

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(1) Many nonradioactive substances can induce cancer in experimental animals (Go77, Ve78). However, for nonradioactive substances found in uranium mill tailings, we do not feel that dose-response relationships adequate for estimating such risks for oral intake have been developed.

6.5 Effects Expected in Plants and Animals

No significant adverse effects are expected in plants or animals from radioactive emissions from the model tailings pile.

No attempt to estimate health effects from toxic materials released from the model tailings pile is made since such estimates require site-specific data on concentrations in water used for irrigation or watering livestock, agricultural practices, and so forth. Data on toxicity and an approach to estimating levels toxic to plants and animals are detailed in Appendix C. In a properly controlled tailings pile, there should be no hazard to plants or animals.

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Ge78 George A.C. and Breslin A.J., "The Distribution of Ambient Radon and Radon Daughters in Residential Buildings in the New Jersey-New York Area," presented at the Symposium on the Natural Radiation in the Environment III, Houston, Texas, April 1978.

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Chapter 7: CONTROL OF TAILINGS DURING MILLING OPERATIONS

Releases of radioactive and nonradioactive hazardous materials from tailings during milling operations are controlled by existing standards and regulations, for the most part. Also, the Act requires that environmental standards for nonradioactive hazardous materials be consistent with standards under the Solid Waste Disposal Act (SWDA), as amended. Therefore, we briefly summarize existing standards and regulations applicable to releases from uranium tailings before we analyze controls for such releases during the operational phase of uranium byproduct material management.

EPA promulgated Environmental Radiation Protection Standards for Nuclear Operations on January 13, 1977 (40 CFR Part 190). These standards specify the radiation levels below which normal operations of the uranium fuel cycle are determined to be environmentally acceptable. Radiation exposure due to releases from uranium byproduct material is included under these standards with the exception of emissions of radon and its decay products. Alternative standards for radon emissions from uranium byproduct material are considered in this Chapter. We also briefly review controls for radioactive releases other than radon for the purpose of determining if the existing standards remain cost effective in requiring their specific protection levels.

EPA promulgated standards for discharges of process waste water from uranium mills on December 3, 1982, as Ore Mining and Dressing Point Source Category; Effluent Limitations Guidelines and New Source Performance Standards, Subpart E - Uranium, Radium and Vanadium Ores Subcategory (40 CFR Part 440). The purpose of these rules is to establish new source performance standards (NSPS) under the Clean Water Act. The NSPS require that "...there shall be no discharge of process wastewater from mills using the acid leach, alkaline leach or combined acid and alkaline leach process for the extraction of uranium or from mines and mills using in situ leach materials."

EPA promulgated Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities under Subtitle C of the Solid Waste Disposal Act (SWDA) on July 26, 1982, (40 CFR Part 264). Radioactive materials controlled under the Atomic Energy Act of 1954, as amended, are not included under the Solid Waste Disposal Act. However, the Act requires that standards for nonradioactive hazards under the Act shall provide for the protection of human health and the environment consistent with the standards required under Subtitle C of the Solid Waste Disposal Act, as amended, which are applicable to such hazards.

The Act also required the NRC to insure that management of uranium byproduct materials is carried out in such a manner as conforms to general requirements established by the NRC, with the concurrence of EPA, which are, to the maximum extent practicable, at least comparable to requirements applicable.to the possession, transfer, and disposal of similar hazardous material regulated by EPA under the SWDA, as amended.

EPA standards under the SWDA, as amended, specify concentration limits for toxic materials in groundwater and also specify that there shall be no increase in background levels in groundwater for hazardous constituents listed in Appendix VIII of 40 CFR Part 261. These rules basically require that: 1) a plastic liner should be placed on the bottom of a tailings pond to prevent seepage of leachate into the groundwater; 2) an active leachate management program should be conducted to treat, process, recycle, etc., the leachate collected from the tailings pond; 3) groundwater adjacent to the liner should be monitored; and 4) a corrective action plan should be implemented if hazardous constituents are detected above background levels in the groundwater.

The Nuclear Regulatory Commission issued rules on October 3, 1980, which specify licensing requirements for uranium and thorium milling activities, including tailings and wastes generated from these activities (10 CFR Part 40). These rules specify technical, surety, ownership, and long-term care criteria for the management and final disposition of uranium byproduct material.

The NRC also enumerated the authorities reserved to the NRC in Agreement States under the provisions of the Act, and specified requirements for Agreement States to implement the Act (10 CFR Part 150). Under the Agreement State program, Agreement States can issue licenses for uranium processing activities, including uranium byproduct material generated from these activities.

7.1 Objectives of Control Measures

Releases of radionuclides and toxic elements to air and water from uranium mill tailings piles during milling operations can be reduced or eliminated by a variety of control measures. Some of these are appropriate for temporary control, and others have a more lasting fect. Releases to air are in the form of windblown tailings dust and don gas. Releases to water are primarily from seepage from tailings nds into underlying aquifers. This section discusses available thods for controlling these releases and the benefits achievable.

.1.1 Wind Erosion

Wind can erode exposed tailings embankments and dry beach areas nd transport small tailings particles away from the site. These eleases cause radiation doses to people living near the tailings pile, rimarily through inhaling the airborne tailings particles. Radiation doses can also occur, but to a lesser extent, from ingesting food contaminated with tailings particles or from external exposure to offsite tailings deposited on the ground. Tailings also contain toxic elements that could be ingested eventually by man and animals or absorbed by plants.

7.1.2 Radon

Since radon-222 is an inert gas, it readily diffuses through the interstitial spaces of a tailings pile to the surface, where it escapes into the air. Radon-222 can cause large radiation doses to the lungs of people living near tailings piles and, because radon can travel long distances through the atmosphere before decaying, it also causes small radiation doses to large numbers of people distant from tailings piles. Control measures can reduce radon emissions from the tailings.

7.1.3 Water Contamination

Wind and water flowing over or through tailings can carry radionuclides and toxic elements to surface or underground water. The primary concern during milling operations is when water seeps from the tailings ponds into an underground aquifer, contaminating the water with radionuclides and toxic elements and presenting potential health risks to people using the water. The objectives of control measures for water protection are to reduce or eliminate seepage from tailings ponds and to prevent the contamination of water resources.

7.2 Control Methods

7.2.1 Wind Erosion

Wind erosion can be controlled by stabilizing tailings by any of the following methods:

1. Physical Methods--wetting the tailings or covering the tailings with soil or other restraining materials.

2. Chemical Methods--treating the tailings with a chemical which interacts with the fine-sized materials to form a crust.

3. Vegetative Methods--growing plants in the tailings or in cover materials.

4. Staged or below-grade disposal.

During the operational phase of a mill tailings pile, airborne-dust is usually controlled by wetting the surface of the tailings or by treating the dry surfaces with chemicals. During the post-operational phase more permanent methods can be used, either physical or vegetative methods, or a combination of these methods. However, vegetative procedures are unsuitable for many locations because of the low rainfall and the high alkalinity or acidity of the tailings.

Keeping tailings surfaces wet with tailings solution or sprinkling them with water can suppress dusting. This can be done, for example, by discharging tailings slurry from multiple discharge points, as opposed to a single point. Alternatively, sprinkling systems or tank trucks can spray dried areas. Because surfaces of the tailings impoundment can dry out rapidly, this method of dust suppression requires continuous attention.

Chemical stabilization involves interaction of a reagent with tailings to form an air- and water-resistant crust or layer that will effectively stop dust from blowing. Resinous adhesives; lignosulfonates; elastomeric polymers; milk of lime; mixtures of wax, tar, and pitch; potassium and sodium silicates; and neoprene emulsions have been used for such purposes (De74). In tests by the U.S. Bureau of Mines, resinous adhesives, lignosulfonates, and elastomeric ploymers were shown to be the most promising chemicals for stabilizing tailings. Calcium lignosulfonate (Norleg A) and an elastomeric polymer (DCA-70) were tested on the tailings at Tuba City, Arizona, with reasonably good results, although periodic maintenance was needed (Ha69). More recently, wood-fiber-based materials (Conwed-200) and magnesium chloride (Dust Guard) have been used effectively for tailings dust control (Ma82). Table 7-1 lists chemicals that have been used for suppressing tailings dust and their estimated unit costs.

Various cover materials have been used or tested for stabilizing tailings and controlling wind erosion, including soil, rock, slag, bark or straw, vegetation, and synthetic covering such as asphalt. The most common cover materials used are soil and vegetation because of their relative ease of application and economy. Although vegetative cover can sometimes be used by itself, it is normally used in conjuntion with soil cover or with a chemical stabilizing agent. However, for areas of low rainfall, vegetative cover will require irrigation.

Table 7-1. Chemical Stabilization Agents Used for Dust Suppression (1981 dollars)

Product	Type	Application Rate	Unit Cost ($/acre)
Aerospray-70	elastomeric polymer	230 gal/acre	$1300
Soil Gard	elastomeric polymer	420 gal/acre	1800
Dust Binder Concentrate	elastomeric polymer	240 gal/acre	1600
Coherex	resinous adhesive	730 gal/acre	900
Norlig A	lignosulfonate	2.4 tons/acre 1.5 tons/acre	270(a) 180(b)
Conwed-200	wood fiber	0.75 tons/acre & 40 lbs/acre	250
Conwed-200 & Terra-Tac 1	wood fiber	0.75 tons/acre 40 lbs/acre	350
Dust Guard	Magnesium Choride	12 tons/acre	850

(a)Based on application rate used by Bureau of Mines (Ha69).
(b)NRC estimate (NRC80).

Several recent tailings impoundment designs have incorporated progressive reclamation schemes into overall tailings management programs. These schemes segment large tailings areas into a number of smaller cells, with sequential construction, filling, and reclamation. Such schemes substantially reduce dust emissions by reducing the available surface area of exposed tailings.

Tailings can also be stored and disposed of through the use of existing open mine pits or special excavations, so that the tailings are below grade, thus virtually eliminating exposure of the tailings to surface erosional effects.

7.2.2 Control of Radon

Radon releases from uranium mill tailings can be controlled by minimizing the exposed dry beach areas of tailings by keeping the tailings covered with water, soil, or some type of synthetic material. Management practices involving staged reclamation of the tailings are also a practical way of limiting the area of exposed tailings.

Radon diffusion through tailings is significantly affected by the moisture content of tailings. Tailings covered by water do not release any significant quantity of radon to air, and the release rate of radon from wet beach areas is only about 25 to 30 percent of the release from dry beach areas (NRC81). For most existing older tailings piles, this method of controlling radon is dependent on the design of the tailings pile and appears to have limited application. Although radon emissions can be reduced somewhat by discharging tailings slurry onto the pile and keeping it wet, large areas of exposed tailings will still exist because of upstream construction methods and the need to maintain adequate freeboard. However, for new or future tailings piles, design and management techniques can be used that will keep all but a small area of the tailings either wet or covered with water (NRC80).

Radon emissions to the atmosphere can be controlled by covering the exposed tailings with soil (see Section 8.3). Relatively thick covers (1 to 2 meters) are needed to reduce radon emissions significantly (see Figure 8-1). Soil covers to reduce radon emissions are more applicable to final disposal of the tailings than as an interim measure to reduce radon emissions during milling operations. Applying soil covers to tailings beach areas during operations is not practical because new beach areas are constantly being formed. Several recent tailings impoundment designs have incorporated progressive reclamation schemes into overall tailings management programs. These schemes segment large tailings areas into a number of smaller cells, with sequential construction, filling, and reclamation. Such schemes substantially reduce radon emissions by reducing the of exposed surface area of tailings.

Land restrictions can prevent people from living near tailings piles and thus reduce the health risks from radon emissions from tailings. The greatest risks occur to people living close to the tailings piles (i.e., 0.5 to 1 mile), with the individual risks decreasing significantly with distance from the pile (see Table 6-1).

7.2.3 Control of Groundwater Contamination

The principal available means for controlling groundwater contamination from uranium mill tailings is using liners in the tailings pond to prevent seepage. This method is primarily applicable to new tailings piles because the liners must be installed when the tailings impoundment is originally constructed, unless the pile is removed and replaced. Other methods for controlling potential groundwater contamination involve removing the pollutants from the tailings liquids or dewatering the tailings before disposal. These methods also are most applicable to new mills. Methods for controlling seepage to groundwater under existing tailings piles are limited to pumping contaminated water back to the tailing pond or to separate, lined evaporation ponds.

Placing compacted clay over the ground surface under a tailings pile will act as a sealant and inhibit seepage from the tailings pond. Furthermore, the ion-exchange characteristics of the clay will further retard the transport of contaminants to the underlying aquifer. The sealing property of clay results from its ability to expand when wet. The expanded clay particles decrease the pore space of the soil, decreasing its permeability.

Many types of synthetic materials can be used as liners to inhibit seepage from tailings ponds, including plastics, elastomers, and asphalt coatings. Plastics and elastomers are usually used with polyester or nylon reinforcement and are flexible liners. Careful preparation of the tailings pond base and of the protective soil layer placed after installation of the liner is necessary to avoid damage to the liner.

Chemical processes which remove pollutants from the tailings solution could be used to control groundwater contamination. For example, removing contaminants from the water by lime neutralization or ion exchange are two such processes (NRC80). Lime neutralization precipitates radionuclides and most toxic elements as insoluble hydroxides. Ion-exchange resin can absorb contaminants from the solution. Information on the practicability of these processes is limited, and such processes generally have not been used in the uranium milling industry in the United States (We80).

Based on available information, using liners appears to be the most practical method for preventing groundwater contamination from tailings piles.

7.3 Cost and Effectiveness of Control Measures for Model Tailings Pile

7.3.1 Control of Wind Erosion of Tailings

During the operational phase of uranium mill tailings piles, wind erosion of tailings may be most easily controlled by spraying the dry beach areas with water or treating those areas with a chemical stabilization agent. During the post-operational phase of a mill tailings pile (i.e., before final disposal), a thin cover may be used to prevent wind erosion. Although many types of cover material are available, soil appears to be the most practicable cover for this purpose. The cost and estimated efficiency of these control methods are shown in Table 7-2.

For new tailings piles, efficient design and management practices can reduce the amount of airborne dust released from the piles. Staged disposal (see Appendix B) can reduce the amount of tailings dust by about 70 percent (NRC80). Below-grade disposal will shield the dry tailings areas from wind erosional effects and significantly reduce the amount of tailings dust. We assign a control efficiency of 90 percent to the below-grade disposal option described in Appendix B. No direct costs are assigned to dust control for these management options, since dust control is obtained at no additional cost when these management options are selected based on disposal considerations. Appendix B contains a discussion of the costs of these management options.

7.3.2 Control of Radon

Methods for reducing radon emissions to air from tailings are not easily applied to existing tailings piles during the operational phase. Using cover materials is not practical since new tailings beach areas are continuously being formed. Although radon emissions can be reduced by enlarging the area of tailings covered by water, such an approach is affected by the design of the tailings pile and is a complex function of seepage, evaporation and recycling rates, and tailings embankment strength and stability. For purposes of subsequent analyses, we conclude that using water covers to obtain large reductions in radon emissions is not generally applicable to existing tailings piles. By wetting the tailings surfaces with tailings liquids or by sprinkling with water, a small reduction (20 percent) in the radon emissions can be achieved (NRC80).

For new tailings piles, the use of staged disposal can reduce radon emissions by about 70 percent. Designs that maximize the amount of tailings covered by water can achieve a greater-than 90 percent reduction of the radon emissions (NRC80). No direct costs are assigned to these methods for controlling radon, since the control is obtained at no additional cost when the management option is selected based on disposal considerations.

7.3.3 Control of Seepage to Groundwater

During the operational phase of the mill, contamination of groundwater can be controlled by using a plastic or clay liner on the bottom and sides of the tailings pond. Estimated costs for a clay liner at a new tailings pond are presented in Appendix B for the model tailings pile as $12 million (1981 dollars), which includes $2 million for overhead and contingencies. The estimated cost for a clay liner at a new tailings pile using the staged disposal method is $8.9 million, which includes $1.5 million for overhead and contingencies. The staged disposal method has a lower estimated cost primarily because the tailings are arranged in a thicker layer than they are for surface storage, thereby reducing the area requiring a liner.

Table 7-2. Costs and Effectiveness of Methods for Controlling Wind Erosion at a Model Tailings Pile (1981 dollars)

Control Method	Capital Costs	Annual Costs	Present Worth	Estimated Control Efficiency (%)
		OPERATIONAL PHASE		
Water Spray (Truck)	--	33	250	50 (NRC80, PE82)
Water Spray (Piped)	400	160	1,220	90 (PED82)
Chemical Stabilization(a)	--	50	380	80 (NRC80, PE82)
		POST-OPERATIONAL PHASE		
Water Spray (Truck)	--	53	48	50 (NRC80, PE82)
Water Spray (Piped)	240	260	260	90 (PE82)
Chemical Stabilization(a)(b)	--	80	73	80 (NRC80, PE82)
Soil Cover (1 foot)	500	--	500	90-100 (PE82)

(a) Cost based on an annual application of the chemical agent, Norlig A.

The estimated 1980 cost of a Hypalon (plastic) liner was $8.25 million (see Alternative 5 in (NRC80)). Correcting this cost to 1981 figures and adding 20 percent for overhead and contingencies, we estimate a plastic liner to cost $10.9 million. This estimate is for the model tailings pond, which has an effective tailings storage area of 80 hectares.

Chemical treatment of tailings at a new tailings pond by the addition of lime is estimated to cost $11.8 million at an acid-leach mill and $10.8 million at an alkaline-leach mill (We80). The alkaline-leach tailings are assumed to be blended with acid-leach tailings before treatment with lime. The key cost item is the sludge storage lagoon for both acid- and alkaline-leach tailings.

Options for protecting groundwater at existing tailings ponds varies from site to site. The control costs for groundwater protection at existing tailings ponds can range from zero, where no action is needed, to the costs of constructing a new, lined tailings pond as presented in Appendix B. An intermediate-cost remedial action is being applied at the Homestake mill in New Mexico. Two rows of wells were drilled across the groundwater hydraulic gradient down from the tailings pond. Water is pumped from wells in the first row, closest to the pond, and recycled. Fresh water is injected into the wells in the second row to dilute any contaminated groundwater. During September 1978, 3.7 million gallons were injected. The estimated present value of the future costs for this pumping is about $85,000, which includes capital costs for 15 pumps and drilling 15 wells and an annual operating cost corrected to present value at a 10 percent discount rate.

The effectiveness of plastic liners results from the physical barrier that these liners provide. A plastic liner will retain all the liquid in the tailings pond, including the dissolved hazardous and toxic materials. This is advantageous since it prevents the seepage into groundwater of chemical forms of these materials that are highly soluble and difficult to remove with chemical processes. It also avails us of the option to issue standards requiring control of materials that are currently not listed under Subtitle C of the SWDA, as amended. Protection of groundwater achieved with plastic liners would control both the hazardous materials listed under Subtitle C of the SWDA, as amended, and other potential pollutants found in uranium tailings.

Molybdenum is found in some uranium ores and is present in tailings after the ore is processed (see Chapter 3). Molybdenum is estimated to be potentially toxic to humans and also has a narrow safety margin, e.g., a low ratio of toxic intake to adult required intake, as discussed in Appendix C. This inorganic has been found in a shallow aquifer at the Cotter mill, Canon City, Colorado, at estimated potentially toxic concentrations, as shown in Chapter 3. Also, molybdenosis has been observed in cattle grazing on land contaminated with molybdenum from the processing of uranium ores in North Dakota and Texas, as noted in Appendix C. All this, in addition to the fact that molybdenum will be controlled by the same methods used to control toxic and hazardous materials, allows us to consider control of molybdenum seepage from uranium tailings storage areas.

Radioactive materials are not included under the SWDA regulations since most of them are controlled under the Atomic Energy Act and thus are exempted by the SWDA, as amended. Tailings contain large quantities of radioactive materials as shown in Chaper 3. Contamination of groundwater by radioactive materials should be controlled since they are potentially the most hazardous constituents of tailings. The same methods used to protect groundwater from other toxic and hazardous constituents will also prevent contamination by radioactive materials.

Concentration limits for toxic materials in the SWDA regulations were adopted directly from the National Interim Primary Drinking Water

Regulations (40 CFR Part 141). Thus, the concentration limits for radionuclides, as specified in the drinking water standards, can be adopted for application to tailings since this is consistent with standards under SWDA, as amended. These include limits of 5 pCi of radium-226 and radium-228 per liter of water and of 15 pCi of gross alpha particle activity per liter of water. The gross alpha particle limit excludes uranium which is present in large quantities in tailings and has been found in high concentrations in shallow aquifers as shown in Chapter 3. However, uranium is indigenous in groundwater in many uranium producing areas. Therefore, rather than specifying a concentration limit for uranium, a nondegradation approach is more suitable. This would require that there would be no increase in the concentration of uranium above background levels in the local area of the tailings.

Protecting groundwater by controlling seepage from tailings with a plastic liner would eliminate seepage as a discharge pathway for excess wastewater. At some sites this is a significant discharge pathway. New Source Performance Standards (NSPS) under the Clean Water Act prohibit the discharge of process wastewater from uranium mills as the degree of effluent reduction currently attainable. Taken together, these controls may pose a problem of what to do with excess waste water at certain locations where average annual precipitation approaches or exceeds average annual evaporation. At these locations the only discharge pathway for excess wastewater would be evaporation. It appears from Table 3-1 that Texas is the only currently developed uranium producing region where this may be a problem.

However, future uranium producing locations may be developed in regions where the average annual precipitation exceeds annual average evaporation. For these situations the NSPS may not apply since these standards were developed for environmental conditions where the average annual evaporation exceeds the average annual precipitation. The standards also contain provisions in the event that the annual precipitation exceeds the annual evaporation. This potential problem may also arise for a new tailings impoundment at an existing uranium processing site. In this case a determination would be required as to whether a new impoundment would be considered a new source.

7.4 Cost-Effectiveness Analyses

7.4.1 Wind Erosion

The levels of risk to the public from dust particle emissions from uncontrolled tailings piles are relatively low. During the operational phase of the model pile, the lifetime risk of fatal cancer to the nearest individuals is estimated to be about 10^{-5}, and the number of cancer deaths in the population from 15 years of dust emissions range from 0.03 for a rural site to 0.001 for a remote site. These risks can be reduced to even lower levels through the use of dust control measures.

Costs and benefits (health risk reductions) for various levels of dust control for the model tailings pile for both the operational and post-operational phases are presented in Tables 7-3 and 7-4, respectively. A combination of chemical stabilization and water sprinkling can achieve a 90-percent reduction in dust emissions. This would result in a reduction from 10^{-5} to 10^{-6} in the lifetime risk of fatal cancer to the nearest individual and will prevent up to 0.03 fatal cancers (in the population living around the tailing pile at a rural site) during the operation phase of the tailings pile, at a cost of $630 thousand. For new tailings, the use of staged disposal in combination with chemical stabilization can achieve a 94 percent reduction in dust emissions. This would result in a reduction of the risks similar to those just described, but at a smaller incremental cost of $114 thousand.

7.4.2 Control of Radon

Costs and benefits for controlling radon emissions during the operational phase of the model pile are presented in Table 7-5. For existing tailings, keeping the tailings surface wet is the only practical control method. Water sprinkling would achieve about a 20-percent reduction in the radon emissions. Over the term of the operational phase this would prevent about 0.7 fatal cancers in the population at a rural site and 0.2 fatal cancers at a remote site, but would result in only a small reduction in the lifetime risk of fatal cancer to the nearest individuals (i.e., from 1×10^{-3} to 8×10^{-4}).

Table 7-3. Costs and Benefits of Various Levels of Control of Dust Emissions for Model Tailings Pile During Operational Phase (1981 dollars)

Controls	Emission Reduction (%)	Present Worth Cost ($1000)	Lifetime Risk to Individual	Fatal Cancers (Cancers/15y) Rural Site	Fatal Cancers (Cancers/15y) Remote Site
None	0	0	1.0E-5	3.0E-2	1.0E-3
A	50	250	5.0E-6	2.0E-2	5.0E-4
B	80	380	2.0E-6	6.0E-3	2.0E-4
A & B	90	630	1.0E-6	3.0E-3	1.0E-4
B & D	94	114	6.0E-7	2.0E-3	6.0E-5

A=Water spray (truck).
B=Chemical Stabilization (Norlig A).
D=Staged Disposal (applicable to new tailings piles only).
Note: See Chapter 4 for description of rural and remote sites.

Table 7-4. Costs and Benefits of Various Levels of Control of Dust Emissions for Model Tailings Pile During Post-Operational Phase (1981 dollars)

Controls	Emission Reduction (%)	Present Worth Cost ($1000)	Lifetime Risk to Individual	Fatal Cancers (Cancers/15y)(a) Rural Site	Remote Site
None	0	0	3.0E-6(a)	2.0E-2	6.0E-4
A	50	48	2.0E-6	1.0E-2	3.0E-4
B	80	73	6.0E-7	4.0E-3	1.0E-4
C	90	500	3.0E-7	2.0E-3	6.0E-5
A & B	90	120	3.0E-7	2.0E-3	6.0E-5
B & D	94	22	2.0E-7	1.0E-3	4.0E-5
C & D	97	150	9.0E-8	6.0E-4	2.0E-5

A=Water spray (truck).
B=Chemical Stabilization (Norlig A).
C=Soil cover.
D=Staged Reclamation (applicable to new tailings piles only).
Note: See Chapter 4 for description of rural and remote sites.

(a) This is the lifetime risk to an individual who lives nearest the pile during the 5-year post-operational period. The risks from the various pathways are adapted from Tables 6-1 and 6-2.

Table 7-5. Costs and Benefits of Various Levels of Control of Radon Emissions from Model Tailings Pile During Operational Phase (1981 dollars)

Controls	Emission Reduction (%)	Present Worth Cost ($1000)	Lifetime Risk to Individual	Fatal Cancers (Cancers/15y)[a]	
				Rural Site	Remote Site
None	0	0	1.0E-3	3.6	1.2
A	20	250	8.0E-4	2.9	1.0
D	70	0	3.0E-4	1.1	4.0E-1
E	90	0	1.0E-4	4.0E-1	1.0E-1
D & E	95	0	5.0E-5	1.0E-1	4.0E-2

A=Water Sprinkling.
D=Staged Reclamation (applicable to new tailings piles only).
E=Below grade disposal in excavated pit with tailing covered with water (applicable only to new mills).
Note: See Chapter 4 for description of rural and remote sites.

[a] Fatal cancers include those occurring in local, regional, and national populations (see Tables 6-1 through 6-6 for the proportions in each).

For new tailings, using staged disposal in combination with below-grade disposal would allow most of the tailings to be covered with water during the operational phase. This method can achieve a high level of radon control (i.e., greater than 95 percent). This would result in a reduction of the lifetime risk of fatal cancer to the nearest individuals from 1 x 10^{-3} to 5 x 10^{-5} and would prevent 3.5 fatal cancers in the population at a rural site and 1.1 fatal cancers at a remote site.

Using water covers or wetting the tailing surfaces are not appropriate radon control methods during the post-operational phase. The purpose of this predisposal period is to allow the tailings to dry out to allow final disposal. The only way to reduce radon emissions during the post-operational phase is to minimize the amount of exposed tailings through the application of staged reclamation. This method is applicable to new tailings only and would reduce the radon emissions during the post-operational phase by 70 percent for the model tailings pile. This would result in a reduction of from 1 x 10^{-3} to 3 x 10^{-4} in the lifetime risk to the nearest individual and would prevent 1.3 fatal cancers in the population at a rural site and 0.4 fatal cancer at a remote site.

7.4.3 Control of Seepage to Groundwater

The benefits of groundwater protection are not easily quantifiable. Maintaining the quality of the groundwater for future uses is the primary benefit of protecting groundwater. At new tailings piles, this can be accomplished by a two-step program:

1. Install a liner to prevent seepage of leachate into the groundwater or, alternatively, select a site with characteristics that have a high probability of protecting groundwater, and

2. Conduct monitoring on a schedule that will assure early identification of any hazardous constituents from the tailings in the groundwater.

The cost of liners ranges from $9 to $12 million to achieve this benefit. The additional cost of selecting a "good" site are anticipated to be small compared with the cost of a liner. The cost of a monitoring program is negligible when compared to liner costs.

At existing tailings piles the benefits of groundwater protection are the same, i.e., preserving the groundwater quality for future uses. Costs, however, can range from small, where groundwater is currently adequately protected due to site characteristics, up to large, when transfer of tailings to a new, lined tailings pond is required to protect groundwater.

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Chapter 8: OBJECTIVES AND METHODS FOR TAILINGS DISPOSAL

8.1 Health and Environmental Protection Objectives

Based on the results in the preceding chapters, we have identified the following objectives for these standards.

1. To prevent future use of tailings in or near buildings. The widespread past use of tailings around foundations or in construction materials has caused an increase of radon decay products in buildings, leading to increased risk of radiation-induced lung cancer.

2. To protect people from radon emanating from tailings piles. Radon exposure of people living in the vicinity of tailings piles leads to increased risk of lung cancer. Also, since radon is a chemically inert gas with a radioactive half-life of 3.8 days, radon released from tailings can travel long distances before it decays. As the radon decays, it exposes large numbers of people to low levels of radiation.

3. To prevent the surface spread of tailings. Tailings may be spread by wind and water. This can cause radiation exposure of local residents from both radon decay products and gamma radiation. In addition, the spread of tailings may contaminate surface water.

4. To protect groundwater. Contamination of groundwater occurs when water comes in contact with tailings or leaches radioactive and toxic materials from the tailings and then moves into a groundwater aquifer through fissures, percolation, or by other means. The degree of risk to man and livestock depends on the concentrations of contaminants in the water and the uses of the water (human consumption, livestock watering, irrigation, etc.).

Because of the long lifetimes of the radioactive contaminants in tailings and the presence of toxic materials (which do not decay), the potential for harming people by any of the above pathways will persist essentially indefinitely. It is therefore necessary to satisfy the above objectives for as long a period as practical. Many factors affect the long-term effectiveness of tailings disposal methods. They include external phenomena, such as erosion by wind and rain, earthquakes, floods, and glaciers; internal chemical and mechanical processes in the piles; and human activities. Predictions of the stability of disposed tailings become less certain as the time period increases. Beyond several thousand years, long-term geological processes and climatic change will govern the effectiveness of most control methods.

These objectives are interrelated. For instance, radon control may be achieved by placing a thick earth cover over the tailings. This method also controls the spreading of tailings, attenuates external gamma radiation, prevents groundwater contamination, and isolates the tailings.

Methods to prevent radon emissions into the atmosphere range from the use of simple barriers to delay the release of radon until it has decayed, to more complex means, such as incorporating tailings into asphalt or concrete, or chemical processing to remove the radium and thorium. Radon control assessment is straightforward and can be quantified for most disposal methods.

Various methods can be used for isolating tailings, ranging from temporary measures, such as fencing, to more permanent measures, such as using a simple earthen cover or deep disposal. Greater amounts of material, such as earth, placed between the tailings and the environment increase the isolation of the tailings. Isolation here means the degree to which man is discouraged from intruding into the tailings.

Protection from external gamma radiation is achieved by placing materials of sufficient mass over the source of the penetrating (gamma) radiation. Thus, a plastic sheet will have essentially no effect on gamma levels, whereas a layer of earth is quite effective.

Methods for control of windblown and precipitation-carried tailings include soil and plastic coverings, chemical and asphalt binders sprayed on the tailings, grading and contouring to eliminate steep slopes, rock covers, and revegetation. Some methods, such as chemical and asphalt sprays, do not last long on tailings and are more suitable for use during the operating phase of a mill.

Methods for preventing contamination of groundwater fall into four groups:

1. Placing a barrier between the tailings and the aquifer which will either prevent the movement of water from the tailings to the aquifer (or vice versa) or will remove hazardous materials by adsorption.

2. Fixing the tailings into a solid mass that prevents the leaching of hazardous materials from tailings by water.

3. Contouring and covering to minimize the movement of precipitation into tailings.

4. Selecting a site that is far removed from aquifers, with characteristics that minimize the movement of water into or out of tailings, and/or that provide natural adsorption of hazardous materials.

Not all these methods are feasible for every tailings pile. Some are only appropriate for new tailings. A significant factor is that most existing uranium mills are located in arid areas of the western United States where natural evaporation generally exceeds precipitation. The selection of a site can eliminate the need for a liner, if the soil has the needed permeability and adsorption characteristics. Disposal methods could also be different for mill sites where abandoned surface mines or natural land depressions are nearby.

8.2 Longevity of Control

Mill tailings will be hazardous for hundreds of thousands of years. Although economically feasible methods which assure control for such long-term periods are beyond present knowledge and experience, we do know enough to provide protection at reasonable cost for periods of hundreds to thousands of years.

Control failures can occur through natural phenomena or through human intrusion. Natural phenomena, such as erosion and deposition, flooding, climatic change, earthquakes, vulcanism, and glaciation can change the landscape. Human disturbance can also take a number of forms, ranging from constructing buildings to drilling, mining, and dam building. Not all of these activities would cause control failures, however; at some sites, human intrusions and natural phenomena may actually increase isolation of the tailings by depositing additional materials or soil on the tailings. The longevity of protection achievable will vary considerably from site to site.

In the following discussion we group controls into two broad classes: those that depend on active institutional maintenance, and those that do not. Active measures include fences, guards, repair of drainage channels, replacement of eroded cover, and maintenance of vegetative cover. Unfortunately, there is no general consensus on the length of time human institutions will remain effective or reliable to continue such active measures. In this regard, failure of institutional controls does not necessarily imply a complete breakdown of societal structure. The more likely situation would be failure of institutional controls through program reductions, reorganization, changes in priorities, or through the failure of special funding mechanisms.

8.2.1 Human Intrusion

The effectiveness of controls in preventing intrusion over long time periods is difficult to evaluate. Probably the worst scenario is the use of tailings as a resource for construction material by residents of a nearby population center. This can (and has) led to widespread use of tailings around, under, and in residences, schools, and other inhabited structures. Any easily removable or attractive control materials have a potential for promoting misuse. Examples are fences and small-sized rock covers.

Prevention of intrusion for long periods is more likely to be successful by using passive methods. Thick earth covers, for example, provide significant long-term passive protection against intrusion. Other effective passive methods include heavy rock cover, deep-mine disposal, below-grade disposal, solidification in a cement or asphalt mixture, or coverings of a tailings-cement mix.

8.2.2 Erosion

All surface disposal methods are subject to erosion. Some representative values for average soil erosion rates in the United States are given in Table 8-1. These erosion rates are averages and thus do not mean that the surface is lowered uniformly by that amount.

Widely varying rates of erosion, and also of deposition, can be found within any drainage basin. High gradient and elevated areas will experience much higher-than-average rates, and depressed areas will, in general, experience deposition, rather than erosion. These rates are most applicable to the below-grade surface disposal option.

Erosion rates for above-grade disposal will be greater. Erosion rates for the Colorado River basin vary between 0.09 and 0.25 meters per 1,000 years. Wind erosion is expected to be much greater for tailings disposed of above grade, depending on the effectiveness of vegetative or other surface treatment. Loss of vegetation will increase water erosion. Rock cover will greatly reduce wind erosion. The maximum rate of erosion occurs in areas with about 10 inches (25 cm) of rainfall per year (Fo71). This annual rainfall is typical of the uranium milling areas in the western United States.

8.2.3 Floods

Floods are probably the greatest natural hazard to the integrity of tailings piles. Piles can be protected against floods by constructing appropriate barriers or by not locating them in flood plains. Some of the measures available for protecting piles left in place are: grading the piles so that the sides of the piles have gradual slopes; providing protective rock covers on the slopes (and on the top if needed); and constructing embankments or dikes on the sides of the piles or at other locations to divert anticipated rapidly moving flood waters. The exposed sides of embankments can be protected by rock. When the vulnerability to floods is so great that disposal in place is inadequate, piles can be moved to less vulnerable sites.

Table 8-1. Soil Erosion Rates in the United States

Erosion Rate (cm/1,000 years)	Measurement Technique	Comments	Reference
6	River load*	Average for U.S.	Ju64
4	River load	Columbia River	Ju64
17	River load	Colorado River	Ju64
5	River load	Mississippi River	Ha75
9	River load	Colorado River	Ha75
5	Radioactive dating	Amount of erosion of volcanic extrusion in southern Utah	Ha75
25	River load	Colorado River	Yo75
5	River load	Average for U.S.	Da76
3	River load	Average for North American continent	Pr74

*River load refers to erosion rate estimates based on the sediment load (dissolved and detrital particles) carried by rivers.

Flood protection design must be based on prediction of infrequent high-magnitude floods.

It is customary to rank the severity of floods in terms of the average time over which floods of a given size or greater may be expected to recur. For example, there will be an average of 5 floods in 1,000 years that exceed the "200-year flood." The maximum probable flood (MPF), on the other hand, is the largest flood that one would expect to occur in a given region in a given climatic era. Historical records are generally of too short a duration to determine the size of such floods. Geomorphic data are most useful for determining the past rate of occurrence of these very large floods (Cob78). When such data are unavailable, the MPF can be estimated from historical records, but such estimates are frequently inadequate.

Another measure of flood severity that is sometimes used as a design criterion is the Standard Project Flood (SPF), which results from the most severe combination of weather and hydrologic conditions that are reasonably characteristic of the region involved, excluding extremely rare combinations.

The "design flood" is the flood adopted as the basis for flood protection for a facility after considering both hydrologic and economic factors. In most areas, the characteristics of relatively short-term floods, such as the 50-year flood, have been well established, and engineers can routinely design facilities to be protected from such events. Where the failure of flood protection systems could result in loss of lives and/or great property damage, however, a design based on the MPF may be justified. The SPF is often considered an appropriate intermediate design basis for situations in which some risk is tolerable, and the added cost of providing greater protection is significant. Fortunately, the differences between these classes of floods is not always great in terms of the projected height of flood waters or the design characteristics required for protection. However, difference in water velocity at different locations can be significant, and protective systems must be designed for the site.

Uncertainties in the performance specifications required may affect the practical design of long-term flood protection systems. The characteristics of very long-term floods, such as the 1,000-year flood, are usually much less certain than those of floods that have recurred frequently during historical periods. Furthermore, because of potential damage from erosion and earthquakes, confidence in the ability of conventional flood protection systems to withstand a flood declines with time. In view of these combined uncertainties, conservatively designed systems are required to satisfy very long-term flood protection requirements.

8.2.4 Longevity of Control

We have chosen two time periods for evaluating the longevity of effective control. A short time period of 100 years was chosen for one case, since this has been proposed as the limit for reliance on institutional controls (EPA78). A period of about 1,000 years was selected for the second case. This case displays the difference between active and passive controls, as well as the expected variation of effectiveness of controls over longer time periods.

In general, the longevity of controls over time can be rated as follows:

Highest
- Deep geological disposal.
- Below-grade surface disposal.
- Above-grade surface disposal, entire area covered with thick earth and rock cover.
- Above-grade surface dispoal, entire area covered with thick earth, slopes covered with rock.
- Above-grade surface disposal, entire area covered with thick earth.

Lowest
- Above-grade surface disposal, entire area covered with thin earth and maintained.

This ranking assumes the tailings pile is located where erosion occurs. If tailings are located where soil deposition is taking place, the ranking will be equal for all cases as long as deposition continues.

8.3 Disposal Methods and Effectiveness

8.3.1 Earth Covers

Earth placed over tailings slows the movement of radon into the atmosphere by various attenuation processes. When the earth is moist, attenuation increases. Different soils have different attenuation properties; these can be quantified in terms of a quantity called the "half-value layer" (HVL). The HVL is that thickness of cover material (soil) that reduces radon emission to one-half its value. Figure 8-1 shows the percentage of radon that would penetrate various thicknesses of materials with different HVLs. These values are nominal; the actual HVL may vary significantly. From Figure 8-1 it can be seen that 3 meters of sandy soil (HVL = 1.0 meters) will reduce the radon released from tailings by about 90 percent. Soils with better attenuation properties would require less thickness to achieve the same reduction. For example, 1 meter of compacted moist soil (HVL = 0.3 meters) would also reduce the radon release by about 90 percent.

A more complete treatment of radon attenuation based on the work of Rogers (Ro81), is given in Appendix P of the NRC Generic EIS for mill tailings. That analysis concludes that the effectiveness of an earthen cover as a barrier to radon depends most strongly on its moisture content. Typical clay soils in the uranium milling regions of western United States exhibit ambient moisture contents of 9 percent to 12 percent. For nonclay soils, ambient moisture contents range from 6 percent to 10 percent. The following table provides, as an example,

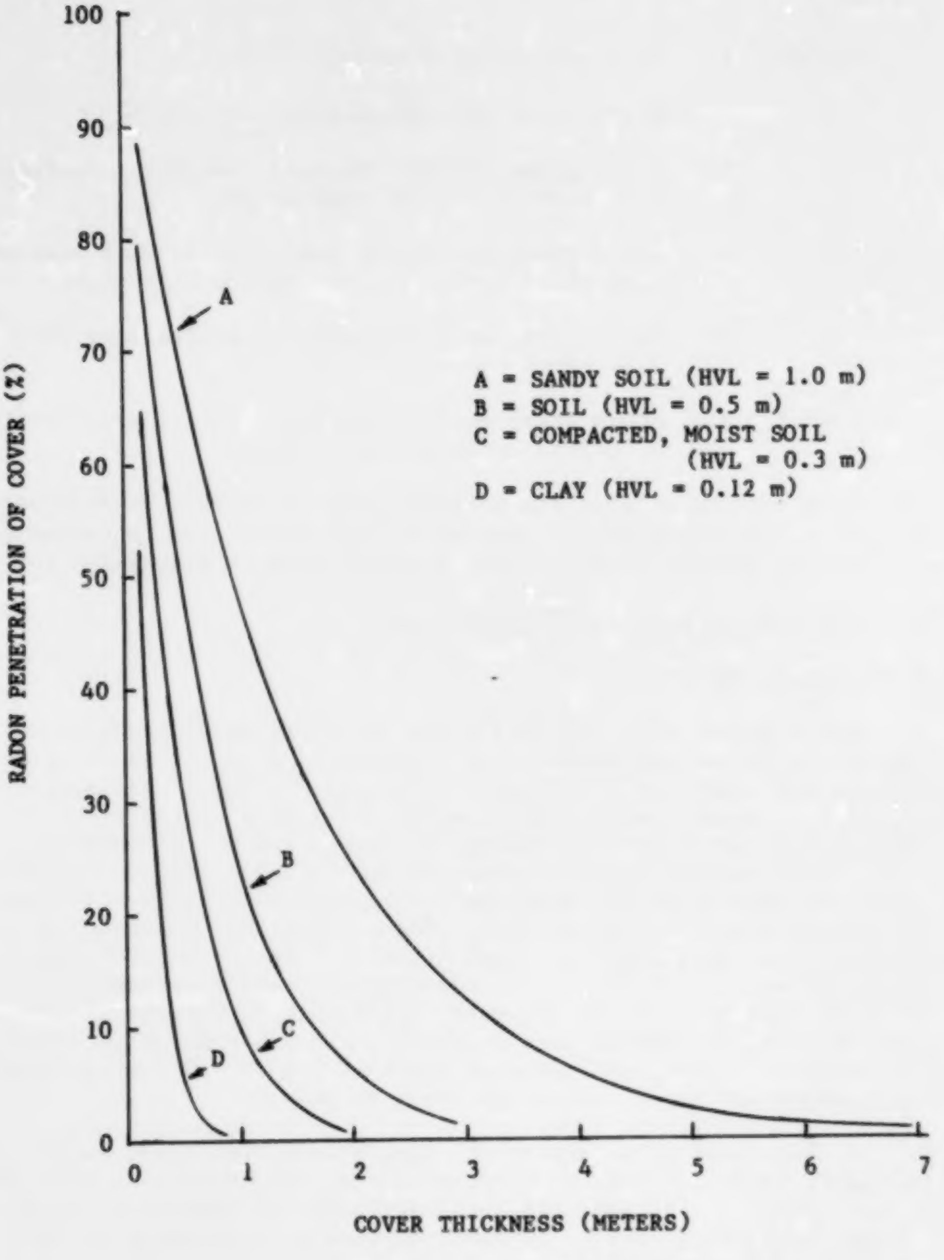

Figure 8-1. Percentage of Radon Penetration of Various Covers by Thickness.

the cover thicknesses needed to reduce the radon emission to 20 pCi/m^2s for the above ranges of soil moisture. Three examples of tailings are shown that cover the probable extreme values of radon emissions from bare tailings at existing sites (100 to 1000 pCi/m^2s); the most common values lie between 300 pCi/m^2s and 500 pCi/m^2s.

Table 8-2. Estimated Earthen Cover Thickness (in meters) to Reduce Radon Emissions to 20 pCi/m^2s

Radon Emission from Tailings (pCi/m^2s)	Percent Moisture Content of Cover 6	8	10	12
100	1.7	1.3	1.0	0.7
300	2.8	2.1	1.5	1.1
500	3.4	2.6	2.0	1.5
1000	4.1	3.2	2.4	1.8

These values are for simple homogeneous covers. In practice, multilayer covers using clay next to the tailings can significantly reduce the total thickness required (Ge81).

The thickness of earthen cover needed to provide isolation is not directly calculable. Perhaps the best approach is to review the depths to which excavations for common activities are made. Excavations are routinely made to 6 to 8 feet for public utilities (water and sewer pipes, power lines, telephone lines). Footings for house foundations are often placed at an 8-foot depth. In colder climates it is important that water lines and foundations be placed below the frost depth to avoid freezing problems. Graves are also dug to a depth of 6 feet or more.

Since digging to or below these depths is common, a significantly greater thickness would be required for isolation against the unlikely event that structures are built on or utility piping is installed at tailings disposal sites. To provide reasonable isolation against such hazards, an earthen cover should have a minimum thickness of 3 meters.

The amount or thickness of earth that will attenuate gamma radiation to one-half its initial value is also called a half-value layer (HVL). As with radon adsorption, the HVL for gamma attenuation depends on soil composition, compaction, moisture content, and other factors. The average HVL of compacted soil for gamma radiation from tailings is about 0.1 meter. Therefore, a soil thickness of 0.5 meter will reduce the gamma radiation to about 3 percent of its initial value from the uncovered tailings, and 1 meter of soil would reduce it to about 0.1 percent of its initial value.

A model tailings pile is assumed to have a radium-226 concentration of 280 pCi/g. This produces a gamma-absorbed dose rate in air of about 4,000 mrad/year on top of the uncovered tailings, assuming a homogeneous distribution of radium-226 in the tailings. An earth covering of 1 meter would reduce this absorbed dose rate in air to about 7 mrad/year. This is slightly less than the total gamma dose from the uranium-238 series under average background conditions.

Earthen covers can also prevent the movement of tailings by wind and water. A combination of grading and contouring slopes, covering with 0.5 meter of earth, landscaping, and continuing maintenance is considered the minimum control for these pathways, as long as maintenance is continued. Longer term protection can be provided by thicker earth covers, and rock or other forms of surface stabilization.

8.3.2 Basin and Pond Liners

Liners are materials placed on the botton of a tailings retention basin or pond to prevent or reduce the seepage of water into the underlying soil. Liners can be made of clays, asphalts, concretes, and polymers (plastics), or various combinations of these (Ba81, Bu81, NRC80).

Agency policy on the use of liners for groundwater protection was delineated in recently promulgated regulations under the Solid Waste Disposal Act (EPA82). A liner placed beneath the waste in a land disposal unit is often a key element of a general liquids management strategy. However, liners are just one component of an overall liquid management system. A liner is a barrier that prevents or greatly restricts migration of liquids into the ground. No liner, however, can keep all liquids out of the ground for all time. Eventually, liners will either degrade, tear, or crack and will allow liquids to migrate out of the unit. It is, therefore, important that liquids be removed during the time that the liner is most effective. Leachate collection and removal systems at landfills and measures to remove free liquids from surface impoundments at closure are the principal techniques used to remove liquids.

The Agency view of the function of a liner contrasts with that of some members of the public and the regulated community. Some view liners as devices that provide a perpetual seal against any migration from a waste management unit. The more reasonable assumption, based on what is known about the pressures placed on liners over time, is that any liner will begin to leak eventually. Others have argued that liners should be viewed as a means of retarding the movement of liquids from a unit for some period of time. While this view accords with how liners do in fact operate, this represents an incomplete regulatory strategy for groundwater protection because it achieves only a delay of the appearance of groundwater contamination rather than a permanent solution. Accordingly, liners should be viewed as a barrier best used to maintain control of liquids prior to their removal from the waste management unit during its active life. Assurance of long-term protection is best achieved by a combination of removal of excess liquids and prevention of influx of new liquids after disposal.

Thus, while liners may remain effective for preventing migration from the unit until well after disposal, their principal role occurs earlier. In final disposal, the Agency believes that a protective cap becomes the prime element of the liquids management strategy. A well-designed and carefully maintained cap can be quite effective at reducing the volume of liquids entering a unit and therefore can substantially reduce the potential for leachate generation at the unit for long periods.

The Battelle Pacific Northwest Laboratory group has performed a comprehensive review of liners (Bu81). They selected seven materials for laboratory testing (Ba81) on the basis of their potential usefulness as liners for uranium mill tailings ponds. These materials were asphalt concrete, asphalt rubber, catalytic airblown asphalt, Hypalon (a chlorosulphonated polyethylene), sodium-bentonite, saline seal-100 bentonite, and GSR-60 bentonite. They also tested a native soil at one of the alternative disposal sites for the Durango, Colorado, inactive tailings pile. The materials were tested for permeability (increased permeability is caused by failures through chemical attack of the asphalts and synthetics or through reduction of the ion exchange capacity of the clays), physical stresses, and radiation damage. Based on laboatory tests, expected field effectiveness, and a cost analysis, the liners selected for field studies were a catalytic airblown asphalt-and-soil amended with sodium-bentonite.

For this analysis, to protect groundwater before the final disposal of the tailings, a 1-meter clay liner must be installed on the bottom and sides of a disposal pit. The clay must have permeability and adsorption properties appropriate for the site and tailings contaminants. Earthen cover is assumed to provide an adequate cap, after disposal, to control influx of water in the arid western regions typical of U.S. uranium mills.

8.3.3 Thermal Stabilization

Thermal stabilization is a process in which the tailings are sintered at high temperatures. The Los Alamos Laboratory has conducted a series of tests on tailings from four different inactive mill sites (Dr81). Tailings were sintered at temperatures ranging from 500° to 1200° C. Tests were then run on the various properties of these tailings. The results are presented in Table 8-3.

Table 8-3. Percent Reduction in Emanating Ra-226 at Temperatures from 500° to 1200° C[a]

Sintering Temperature (°C)	Shiprock, N.M., Pile[b] Sands (%)	Shiprock, N.M., Pile[b] Fines (%)	Durango, Colo., Pile[b] Sands (%)	Durango, Colo., Pile[b] Fines (%)
500	15	16	48	61
600	29	27	64	68
700	44	37	76	80
800	63	58	87	88
900	83	84	92	91
1000	92	96.1	95.5	92
1100	96.4	98.8	99.0	99.8
1200	97.7	99.2	99.5	99.8

[a] $[1 - \frac{\text{treated tailings}}{\text{untreated tailings}}]100\%$

[b] Original emanating Ra-226:

Shiprock sands = 39 pCi/g.
Shiprock fines = 214 pCi/g.

Durango sands = 140 pCi/g.
Durango fines = 473 pCi/g.

These results indicate that thermal stabilization can be quite effective in preventing the release (emanation) of radon from tailings. The authors note that before thermal stabilization can be considered as a practical disposal method, information is needed on the following:

1. The long-term stability of the sintered material exposed to physical degradation and chemical attack (e.g., solubility of new minerals and amorphous material found in thermally stabilized tailings).

2. The interactions of the tailings and the refractory materials lining a kiln.

3. The gaseous and particulate emissions produced during sintering of tailings.

4. Revised engineering and economic analysis as more information is developed.

Since gamma radiation is still present, protection against the misuse of sintered tailings is still required. While the potential health risk from external gamma radiation is not as great as that from the radon decay products, it can produce unacceptably high exposure levels in and around occupied buildings. Also, the potential for groundwater contamination may require the use of liners.

8.3.4 Chemical Processing

The Los Alamos National Laboratory has also studied various chemical processes to remove thorium-230 and radium-226 from the tailings, along with other minerals (Wm81). After removal from the tailings, the thorium and radium can be concentrated and fixed in a matrix such as asphalt or concrete. This greatly reduces the volume of these hazardous materials and allows disposal with a higher degree of isolation than economically achievable with tailings.

The NRC has considered the processing of uranium ore in a nitric acid mill (NRC80). This chemical process would strip a large fraction of the thorium and radium from the ore, along with uranium and other minerals. The thorium and radium would then be concentrated, fixed in a matrix, and disposed of in a manner similar to the process just described for sulfuric acid treatment of the tailings.

The major question regarding both these processes is whether they reduce the thorium and radium values in the stripped tailings to safe levels. If processing efficiencies of 80 percent to 90 percent were attained, radium concentrations in tailings would still be in the 30 to 60 pCi/g range. This concentration can cause excessive levels of radon decay products in occupied structures if these treated tailings were placed under or around the structures. Thus, careful disposal of the stripped tailings would still be required to prevent misuse. Another disadvantage of chemical processing is the cost, although some of the costs might be recovered from the sale of other minerals recovered in the processing (Th81). The value of other minerals can be expected to vary greatly (Th81) from ore to ore.

8.3.5 Soil Cement Covers

A mixture of soil and Portland cement, called soil cement, is widely used for stabilizing and conditioning soils (PC79). It is used to condition subsoils under highway pavements, to serve as a base for large parking lots where it is covered with asphalt, and to stabilize slopes by preventing erosion, among other uses.

The aggregate sizes of tailings appear suitable to make a good quality soil cement, which is relatively tough, withstands freeze/thaw cycles, and has a compressive strength of 300 to 800 psi. When combined in a disposal system with a 1-meter earth cover over it, soil (tailings) cement would be likely to provide reasonable resistance to erosion and intrusion, to substantially reduce radon releases, and to shield against penetrating radiation. Its costs are expected to be comparable to those of thick earth covers.

The long-term performance of soil cement is unknown, especially as tailings piles shift or subside with age. Also, soil cement cracks at intervals when placed over large surface areas. The importance of this cracking on the effectiveness of soil cement has not been evaluated, but is expected to be small.

8.3.6 Deep-Mine Disposal

Disposal of tailings in worked-out deep mines offers several advantages and disadvantages compared to surface disposal options. The probability of intrusion into and misuse of tailings in a deep mine is much less than that achievable with surface disposal. Radon releases to the atmosphere would be eliminated, for practical purposes, as would erosion and external radiation.

The greatest problem with deep mine disposal is the potential contamination of groundwater. This problem is most difficult to evaluate, especially over the long term. Also, this method would be cost-effective for only those mills near deep mines because of the high cost of transporting tailings.

8.3.7 Solidification in Concrete or Asphalt

This disposal method separates the sands fraction of the tailings from the slimes fraction. The sands make up the greatest part of the tailings weight, while most of the radioactive material is in the slimes. After separation, the sands are washed and discharged into a surface pit. The slimes are separated from the water, dried and then solidified in concrete or asphalt. The solidified slimes can then be disposed of in the pit with the sands or by other methods offering more isolation. The NRC analyzed this method in some detail, including a cost evalution (NRC80).

Since about 15 percent of the radioactivity is in the sands, this fraction will contain about 40 pCi/g of radium-226.
This concentration can lead to an excessive buildup of radon in structures if these sands are misused under and around structures. Thus, the sands fraction will require a barrier, such as an earth cover, to isolate them and to prevent misuse . Also, since toxic metals will be present in both fractions (Coa81), a liner may be needed to protect groundwater from the sands fraction.

Overall, this method is costly, provides a relatively high level of protection from 85 percent of the radioactivity in the tailings, but provides little protection from the remaining radioactivity and toxic materials unless additional controls are used.

8.4 Selection of Disposal Method For This Analysis

Earthen covers were selected for analysis for the following reasons:

1. Thick earthen covers are effective in preventing misuse of tailings, in reducing radon emissions, in protecting groundwater for long-term periods, and in resisting erosion.
2. Thick earthen covers can be made long lasting by stabilizing the surface with vegetation and/or rock.
3. Costs are relatively low and can be estimated with some degree of certainty.

An option providing a very high degree of protection was also selected for the analysis. In lieu of any clearly superior disposal method, regardless of cost, the solidification method was chosen.

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Chapter 9: ALTERNATIVE STANDARDS FOR TAILINGS DISPOSAL

In this chapter we first consider the various quantities which can be used to express limitations on environmental releases. We then formulate alternative standards that accomplish, in varying degrees, the objectives set forth in Chapter 8. Finally, we determine the cost of controls required to implement each of these alternatives.

9.1 Form of the Standards

9.1.1 Dose or Exposure Rate Limits

Health protection standards based on radiation dose or exposure have two major advantages. First, the health risk to an individual can be limited directly. Second, the cumulative risk from all pathways to humans from the source is included. Partly because of these advantages, the Federal Radiation Council Radiation Protection Guidance for Federal Agencies (FRC60) and the Environmental Radiation Protection Standards for Uranium Fuel Cycle Operations (40 CFR 190) (EPA77), with the exception of the standards for certain long-lived radionuclides, are in this form.

However, dose or exposure rate limits are not useful in establishing health protection standards in connection with the disposal of uranium mill tailings because they have an inadequate relationship with some of the principal objectives of disposal, such as preventing misuse of the tailings and controlling radon emissions from tailings for a long period of time. Establishing an environmental dose rate limit (or Working-Level Limit) near a tailings pile gives no assurance of providing a long-lasting barrier controlling radon or of inhibiting the use of tailings. In addition, limits on dose imply a need to know the locations of individuals for long periods of time into the future. Unless an exclusion area can be maintained indefinitely, conformance to a dose limit could not be assured.

9.1.2 Concentration Limits in Air and Water

The primary advantage of standards specifying concentration limits of hazardous or toxic materials in air or water is ease of compliance. Most monitoring involves measurements of concentrations in environmental media. Thus, monitoring results can be compared to concentration limits to determine compliance. This is a useful approach in evaluating the performance of emissions and effluent controls at operating facilities.

Concentration limits of radon in air can assure a given level of performance of control measures. The relationship between radon emissions from a pile and offsite concentrations of radon in air is presented in Chapter 5.

Concentration limits are appropriate for the water pathway; EPA groundwater protection policy, which dictates the form of groundwater standards specifies concentration limits.

9.1.3 Release Rate Limits

This form of standard is useful for controlling emissions when either total quantities discharged or ambient levels of a pollutant are of concern. It is also useful for controlling emissions and effluents when it is desirable to force a specific level of control.

Because of these advantages a release rate limit approach appears to offer the best choice of accomplishing the primary objectives of these standards. A release rate limit can assure that an effective and durable barrier controls radon emissions and isolates the tailings from the environment. This barrier can also provide significant assurance that the tailings would not be removed from the site and used in and around occupiable structures.

9.1.4 Engineering/Design Standards

Engineering or design standards specify methods or procedures and the critical dimensions or characteristics of the method. Such standards have the advantage of directly assuring a solution of the problem. For tailings disposal, a design standard could require that tailings be covered with a certain type of soil to a minimum thickness and with a maximum slope. Soil stabilization methods could also be spelled out, such as rock cover on the slopes and vegetation over the remainder of the disposal site.

Several disadvantages are inherent in design standards. They tend to squelch ingenuity and initiative to develop improved and less costly methods. They do not reflect the variations in local conditions that may lead to greater health protection if properly utilized or exploited. They are difficult to change or modify. The disadvantages of design standards appear to outweigh the advantages for use in the disposal of uranium mill tailings. In addition, the legislative history of the Act does not support the use of such standards.

A second approach in engineering/design standards can be based on probabilities considerations. In this form, the primary objective of the standard is stated clearly. Then probabilities (in quantified terms) are assigned for achieving the primary objective during various future periods. For example, in the near term, the numerical probability assigned to meeting the primary objective could be high. For longer periods, the probability could be reduced, reflecting inability to predict the effectiveness of controls over longer times.

Compliance with a probability-based standard uses models, which project the future performance of control methods, and expert views. The advantage of this approach is that it forces an appraisal of the long-term hazards associated with the tailings. However, the present state of the art for tailings disposal does not permit the use of numerical probability-based design standards.

9.2 Alternative Disposal Standards

We have evaluated a range of alternatives for disposal standards based on the objectives described in Section 8.1, the most likely disposal method chosen in Chapter 8, and the form of the standard considered in Section 9.1. These alternatives are presented in Table 9-1. The requirements selected to meet the objectives are shown for each alternative. Most of the requirements are expressed quantitatively, and in combination they achieve the overall objective of reducing risks to people from tailings. The ranges of the controls vary widely, from no control (Alternative A) to high levels of control (Alternatives E and F).

Uranium mill tailings will remain hazardous for hundreds of thousands years due to the 75,000-year half-life of thorium-230. Protecting public health for such periods of time is difficult to conceptualize, much less assure. On a practical basis, controls reasonably can be relied on for periods defined as:

- Active control--a maximum period of about 100 years.
- Available and practical engineering controls--a period extending from a few hundred years to perhaps 1,000 years.
- Controls featuring great isolation--a period of thousands of years limited by major geological activity.

These periods will be used in the ensuing discussions of alternative standards.

Alternatives A through F were designed to consider 6 progressively more stringent levels of protection.

Alternative A. This alternative is the "no standards" case and represents conditions if nothing is done. The piles will remain hazardous for a long time, taking about 265,000 years for the radioactivity to decay to 10 percent of current levels. The radon

Table 9-1. Alternative Standards for Disposal of Uranium Mill Tailings

Alternative Standard	Minimum Time Controls Should Prevent Erosion and Misuse (years)	Radon Emissions Permitted from Top of Pile (pCi/m^2-sec)	Expected Time Controls Should Protect Groundwater (years)
A	None	No limit	None
B	100 (with institutional controls)	No requirement	100
C	Indefinite	60	> 100
D	200-1,000	20	1,000
E	1,000	20	1,000
F	> 1,000	2	> 1,000

emission rate from a model pile is estimated to be 280 pCi/m^2s, compared to a background rate for typical soils of about 1 pCi/m^2s. We also know that the concentration of some toxic chemicals in the tailings is hundreds of times background levels in ordinary soils, so that the potential for contaminating groundwater is present and continues indefinitely.

Alternative B. This alternative specifies that control measures include a durable cover that is subject to inspection and maintenance requirements for 100 years. Institutional controls (inspection and maintenance) would also be required to prevent significant contamination of groundwater, or groundwater would be treated before use. No radon emission rate is specified.

Alternative C. The number of years over which the integrity of control measures shall be designed to be maintained is not specified, but controls should be chosen to endure without near-term maintenance; they would thus remain effective for an "indefinite time." The radon emission limit specified is 60 pCi/m^2s. Control measures used to meet this limit should prevent significant contamination of groundwater for a few hundreds of years.

Alternative D. In this alternative control measures are designed to be effective for 1,000 years, and in any case for at least 200 years. The radon emission limit is 20 pCi/m^2s. Water quality is to be maintained so that current uses can be continued and potential uses preserved. This is accomplished by specifying concentration limits in groundwater for toxic substances and by not allowing any increase above existing concentrations for hazardous constituents.

Alternative E. Control measures are designed to be effective for 1,000 years. The radon emission limit is 20 pCi/m^2s. Water quality is to be maintained so that current uses can be continued and potential uses preserved. This is accomplished by specifying concentration limits in groundwater for toxic substances and by not allowing any increase above existing concentrations for hazardous constituents.

Alternative F. Control measures are designed to be effective for at least 1,000 years. The radon emission limit is 2 pCi/m^2s. Water quality is to be maintained so that current uses can be continued and potential uses preserved. This is accomplished by specifying concentration limits in groundwater for toxic substances and by not allowing any increase above existing concentrations for hazardous constituents.

9.3 Estimated Costs of Methods for Alternative Standards

Costs are estimated for the levels of control which will satisfy the levels of health protection shown in Table 9-1. A range of thicknesses of earth covers provides the various protection levels.

Various protective materials are used to increase the long-term effectiveness of the cover. Table 9-2 depicts the relationship between the Alternative Standards and the disposal methods considered. Detailed cost estimates are given in Appendix B.

Because the large differences in the sizes of existing tailings piles at licensed sites can lead to large cost differences, these piles have been separated into three groups: 2 million tons (MT), 7 million tons, and 20 million tons. Their characteristics are given in Appendix B. This grouping is for costing purposes only. While the divergence in estimated costs for existing piles is great, the range in potential health risks is small. Estimates of potential health risks are largely dependent on the area covered by the tailings. The area of the model pile (Chapter 4) and a listing of existing piles (Chapter 3) indicate the areas vary by a factor of only about two:

	Area (hectares)	Ratio of Area of Existing Piles to Area of the Model Pile
Model pile	100	1.0
Existing 2 million tons	48	0.48
Existing 7 million tons	56	0.56
Existing 20 million tons	98	0.98

Thus, potential health risk estimates can be treated uniformly, regardless of the pile size.

9.3.1 Disposal Methods for Existing Tailings Piles

Method ET1

The edges of the square tailings pile are graded and contoured to a 5:1 (H:V) slope. The entire area is then covered with 0.5 meters of earth obtained nearby. A 6-feet high, 6-gauge aluminum chain link fence is placed around the exclusionary zone, which is assumed to be 0.5 kilometer from all sides of the pile. The covered pile is landscaped, assuming that suitable loam or topsoil is available onsite. The borrow-pit is reclaimed. Maintenance and inspection are added for a 100-year period.

Method ET2

The sides of the tailings piles are graded to 5:1 (H:V) slope. The tailings are covered with 1 meter of earth obtained locally and the slopes are covered with 0.5 meter of rock cover. There is no maintenance and inspection of the pile. A fence is installed to form an 0.5-kilometer exclusion area around the disposed tailings. The borrow pit is reclaimed.

Table 9-2. Control Methods Assumed to Satisfy the Alternative Standards

Alternative	Control Method
A	NT1
B	NT2 and ET1
C	NT3 and ET2
D	NT4 and ET3
E	NT5 and ET3
F	NT7 and ET5

NT New Tailings. ET Existing Tailings.

Method ET3

For this method the sides of the square tailings pile are graded to a 5:1 (H:V) slope. The entire tailings area is covered with 3 meters of earth obtained locally. Then the slopes are covered with 0.5-meter rock, and the tailings are landscaped. No fence is necessary. The borrow pit is reclaimed.

Method ET4

The sides of the tailings piles are graded to a 8:1 (H:V) slope, then the entire area is covered with 3 meters of earth obtained nearby. The slopes are coverd with 0.5-meter rock, and the tops of the tailings are landscaped. No fence is needed. The borrow-pit is reclaimed.

Method ET5

The edges of the tailings piles are contoured to a slope of 8:1 (H:V). The entire area is then covered with 5 meters of earth obtained locally. The slopes are covered with 0.5-meter rock, and the tops of the tailings are landscaped. No fence is necessary. The borrow-pit is reclaimed.

Method ET6

The sides of the tailings piles are graded to a 5:1 (H:V) slope. The entire area is then covered with 1 meter of earth obtained locally, after which a cover of 0.5-meter rock is added to the entire pile. A fence is installed to form an 0.5-kilometer exclusion area around the disposed tailings. The borrow pit is reclaimed.

Method ET7

This disposal method provides for below-surface disposal of tailings, with a 3-meter earth cover over the tailings and a 1-meter clay liner below the tailings. For the 2-million-ton pile, a 366-meter square pit is excavated to a 12-meter depth adjacent to the pile. The bottom of the pit is assumed to be above the groundwater table. The pit is lined with 1 meter of purchased clay hauled 3.2 kilometers. The tailings are moved into the pit with scrapers, after which they are covered with 3 meters of the excavated earth. The disposal area is landscaped. The area covered by excess excavated earth is restored. The disposal pit for the 7-million-ton pile is 614 meters square by 15 meters deep, and the pit for the 20-million-ton pile is 1,047 meters square by 15 meters deep. Both pits are assumed to be above the groundwater table. Because of the large sizes, hauling by trucks for an average off-road distance of 3.2 kilometers is assumed. The disposal method and landscaping are similar to those of the 2-million-ton case.

9.3.2 Disposal Methods for New Tailings Piles

Method NT1

This method is the same as the base case in the NRC analysis (NRC80). An initial square basin would be formed by building low earthen embankments along each side, 947 meters in length at the centerline. The mill tailings would be slurried into the basin, and as the basin filled, the coarse fraction of the tailings (sands) would be used to raise and broaden the embankments. The final dimensions of the embankments would be 10 meters high and 13 meters wide at the top. When the mill ceases operations, no control measures for disposal would be applied.

Method NT2

This method is similar to ET1, since both use a thin earth cover on the tailings and rely on institutional controls for maintenance and to prevent misuse. A pit is excavated close to the mill and measures 930 meters square by 2 meters deep. Embankments are constructed along each side, 947 meters long, 10 meters high, and 13 meters wide at the top. The pit is lined with 1 meter of clay obtained locally. Tailings are pumped directly into the pit during operation of the mill. It is assumed that water from the pond will be recycled to the mill, thereby negating the need for an evaporation pond.

At the end of mill life, the embankments are excavated and placed on top of the tailings to a depth of 0.5 meters. The slopes of the covered tailings are graded to 5:1 (H:V). The entire area is landscaped. A fence is placed around the disposal area and provides a 0.5-kilometer exclusion zone. The site is maintained for 100 years by irrigation of the vegetative cover and inspection and repair of the earth cover and fence.

Method NT3

This method is similar to ET2, since both use a 1-meter earth cover and 0.5-meter rock to cover the slopes. A pit is prepared and used in the same manner as that described for method NT2.

At the end of mill life, the embankments are excavated and placed on top of the tailings to a depth of 1 meter. The slopes of the disposed tailings are graded to 5:1 (H:V) and then covered with 0.5-meter rock. The top of the disposed tailings area (that part not covered with rock) is landscaped. A fence is constructed around the site at a distance of 0.5 kilometers from the edge of the disposed tailings.

Method NT4

This method is similar to ET3, since both use 3 meters of earth cover and 0.5-meter rock to cover the slopes. A pit is excavated, prepared, and used in the same manner as that described for method NT2.

At the end of mill life, the embankments are excavated and placed on top of the tailings. Additional earth cover is obtained from a nearby borrow-pit so that the final earth cover over the tailings is 3 meters deep. The slopes of the covered tailings are graded to 5:1 (H:V) and are covered with 0.5-meter rock. The top of the earth-covered tailings is landscaped. The borrow-pit is reclaimed.

Method NT5

This method is somewhat similar to the staged or phased disposal method described by the NRC's GEIS (NRC80). This method uses 6 pits, 300 meters square and 13 meters deep. Two pits are constructed initially and lined with 1 meter of clay. Tailings are pumped to the first pit until it is full and then pumped to the second pit. When the first pit is sufficiently dry, the third or fourth pit is excavated, and the excavated earth is used to cover the first pit to a depth of 3 meters up to the original contour. This process continues sequentially until the end of mill life. An evaporation pond is needed in this method. Costs for this pond are taken from the NRC Generic EIS and corrected for inflation.

At the end of mill life there are four completed pits, which are covered with 3 meters of earth to the original ground contour, and 2 uncovered pits. When sufficiently dry, these last two pits are covered with 3 meters of excavated earth to the original ground contour. The disposal area is landscaped. The areas covered by the evaporation pond and excess excavated earth are restored.

Method NT6

This method is the same as Alternative 7 in the NRC GEIS (NRC80). The tailings are pumped to the edge of a depleted mine pit, where the sands (coarse fraction) and slimes (fine fraction) are separated. The sands are washed, dried, and deposited in the mine pit. The slimes are partially dried, mixed with cement, and deposited in the mine pit where the cement and fine slurry would harden.

Method NT7

This method is similar to ET5, since both use a 5-meter earth cover and 0.5-meter rock to cover the slopes. A pit is excavated, prepared, and used in the same manner as that described for Method NT2.

At the end of mill life, the embankments are excavated and placed on top of the tailings. Additional earth cover is obtained from a nearby borrow-pit so that the final earth cover over the tailings is 5 meters deep. The slopes of the covered tailings are graded to 8:1 (H:V) and are covered with 0.5-meter rock. The top of the earth-covered tailings is landscaped. The borrow-pit is reclaimed.

Cost Estimates

Cost estimates for the disposal of tailings at active uranium milling sites are presented in Table 9-3 along with a summary of critical design features. The cost estimate details are developed in Appendix B, which also includes characteristics of tailings piles, unit costs, and descriptions of disposal methods (NT-1 to 7 and ET-1 to 7).

All cost estimates in Table 9-3 include an increase of 20 percent for contingency, overhead, and profit, but do not include the cost of a liner for the tailings pond. The disposal costs for the model pile are greater than for the existing 7-MT pile. The difference is due to the larger size of the model and the costs of preparing the initial tailings impoundment. The model pile, taken directly from the NRC Generic EIS (NRC80), appears oversize when compared with industry practice. This leads to the considerably greater costs for the model pile when compared to an existing pile containing about the same quantity of tailings. These cost estimates for the NT methods can be considered maximum costs.

Table 9-3. Summary of Cost Estimates for Disposal of Active Uranium Mill Tailings

Method	Cost[a] (1981 dollars in millions)			Maximum slope	Cover thickness (m)	Rock cover (0.5 m)	Vegetation cover	Below grade disposal
NEW TAILINGS								
NT-1[b]	1.2			-	-	-	-	-
NT-2[c]	13.8			5:1	0.5	-	Yes	-
NT-3[d]	15.4			5:1	1.0	On slopes	Yes	-
NT-4	21.5			5:1	3.0	On slopes	Yes	-
NT-5[e]	27.0			-	3.0	-	Yes	Yes
NT-6[f]	91.2			-	3.0	-	Yes	Yes
NT-7	31.9			8:1	5.0	On slopes	Yes	-
EXISTING TAILINGS								
	By pile size (MT)							
	2	7	20					
ET-1[c]	3.9	5.7	11.1	5:1	0.5	-	Yes	-
ET-2[d]	3.8	7.0	14.4	5:1	1.0	On slopes	Yes	-
ET-3	6.9	11.4	22.3	5:1	3.0	On slopes	Yes	-
ET-4	7.6	13.9	29.2	8:1	3.0	On slopes	Yes	-
ET-5	11.9	19.9	40.6	8:1	5.0	On slopes	Yes	-
ET-6[d]	12.8	17.4	32.5	5:1	1.0	Total area	-	-
ET-7[g]	10.3	38.4	111.7	-	3.0	-	Yes	Yes

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[a] Costs include a 20 percent increase for contingencies, overhead, and profit, but do not include the cost of a tailings pond liner.

[b] Base case; no disposal.

[c] Fenced and maintained.

[d] Fenced.

[e] Phased disposal.

[f] Solidified in concrete/asphalt.

[g] Pile is moved.

9.4 Accidental and Radiation-Induced Deaths from Disposal

One of the costs of control is the possibility of accidental deaths during the disposal of tailings and when moving tailings. Table 9-4 shows our estimate of the number of accidental deaths that could be associated with each alternative disposal standard. These estimates include accidental deaths of workers and premature, radiation-induced deaths of construction workers at the tailings sites.

In our review of the existing tailings sites, we identified only two sites that may be vulnerable to flooding. Even for these two sites, it is not clear that the tailings would have to be moved to provide protection against flooding. Thus, we have made no estimate of the number of deaths that might occur, primarily to workers and the public, from transportation accidents if the tailings piles are moved.

The most important parameter in this simplified analysis of accidental deaths is the number of person-hours of labor required to do the job. This is used to estimate the number of construction-related deaths, as well as the number of premature deaths from radiation exposure.

The labor required for piles that are to be controlled onsite is proportional to the amount of earthmoving to be done; a gradual slope requires more earthmoving than a steep slope, roughly in proportion to the ratio of the slopes, and a thick cover requires more earthmoving than a thinner one. Based on figures from a DOE contractor (DeW81), we estimate that Alternative NT2 would require about 110 person-years of labor for the model pile. The labor requirements for Alternative NT3 would be 220 person-years; for NT4 and NT5, 280 person-years; and for NT6 about 200 person-years, assuming the solidified tailings would require some cover. The labor requirements for each ET alternative are estimated by scaling directly by the area covered by the tailings (see Section 9.3), using an effective area of the model pile of 80 hectares.

The occupational deaths resulting from this are estimated from mortality statistics for the construction industry: 60 deaths per 100,000 worker-years (NS78). This corresponds to 6×10^{-4} accidental deaths per person-year.

Radiation-induced deaths are difficult to estimate since it is impossible to anticipate measures that might be used to protect workers. However, in the worst case, the gamma radiation exposure rate over a bare tailings pile (typically 1 mrem/h) for a working year would lead to exposures of about 2 rem/y. Inhalation of radon decay products would, at most, lead to a comparable risk. In Table 9-4, we have assumed that the maximum risk of premature, radiation-induced death is equivalent to the risk from an exposure of 4 rem (whole-body equivalent) of gamma radiation per person-year of labor. Radiation-induced deaths are estimated at the rate of 2×10^{-6} per person-rem. Since radiation exposures will be significantly reduced as the earth cover is added, the radiation-induced death estimate was taken as one-half the value obtained without credit for shielding by the cover.

Table 9-4. Accidental and Radiation-Induced Deaths Associated with Alternative Levels of Tailings Control

Method	Accidental Deaths	Radiation-Induced Deaths
	NEW TAILINGS	
For a Model Pile		
NT2	0.07	0.04
NT3	0.13	0.09
NT4 and NT5	0.17	0.11
NT6	0.12	0.08
NT7	0.19	0.13
	EXISTING TAILINGS (As of January 1980)	
For 2-million-ton piles: (10 piles)		
ET1	0.4	0.3
ET2 and ET6	0.8	0.6
ET3 and ET4	1.0	0.7
ET5	1.2	0.8
For 7-million-ton piles: (10 piles)		
ET1	0.5	0.3
ET2 and ET6	1.0	0.6
ET3 and ET4	1.2	0.8
ET5	1.4	0.9
For 20-million-ton piles: (3 piles)		
ET1	0.2	0.2
ET2 and ET6	0.5	0.3
ET3 and ET4	0.6	0.4
ET5	0.7	0.5
TOTAL:		
ET1	1.1	0.8
ET2 and ET6	2.3	1.5
ET3 and ET4	2.8	1.9
ET5	3.3	2.2

REFERENCES

DeW81 Telephone conversation between Michael DeWitt, Sandia National Laboratories, Albuquerque, New Mexico, and EPA staff, 1981.

EPA77 Environmental Protection Agency, "Environmental Radiation Protection Standards for Nuclear Power Operations (40 CFR 190)," January 1977.

EPA82 Environmental Protection Agency, "Hazardous Waste Management System; Permitting Requirements for Land Disposal Facilities (40 CFR Part 264)," July 26, 1982.

FRC60 Federal Radiation Council, "Radiation Protection Guidance for Federal Agencies," Federal Register 4402, May 18, 1960.

NRC80 Nuclear Regulatory Commission, "Final Generic Environmental Impact Statement on Uranium Milling," NUREG-0706, USNRC, Washington, D.C., 1980.

NS78 National Safety Council, "Accident Facts," 444 N. Michigan Ave, Chicago, Illinois.

Chapter 10: ANALYSIS OF COSTS AND BENEFITS FOR ALTERNATIVE TAILINGS DISPOSAL METHODS

10.1 Benefits Achievable Through Disposal of Tailings

The estimated benefits of disposal of tailings include:

1. Reducing the likelihood of misuse of tailings, and the resulting risk of lung cancer deaths from inhaling radon decay products.

2. Reducing the risk of lung cancer deaths caused by radon and its decay products.

3. Reducing the contamination of water with radioactive and other hazardous or toxic materials.

4. Reducing the spread of radioactive and other hazardous or toxic materials.

5. Eliminating, for practical purposes, exposure to gamma radiation from tailings.

All of these benefits are achieved by stabilizing the tailings by adding earthen cover material and instituting protective measures for groundwater, where needed.

The benefit we are best able to quantify is the number of lung cancer deaths averted by controlling radon emissions. We can estimate the reduction in radon emissions resulting from the placement of a given thickness of earthen cover, and translate this reduction into lung cancer risk averted (see Chapter 6). The benefits of radon control are quantified for both the total risk to populations of lung cancer death that is averted and for the reduction in risk to individuals living near the piles. These benefits are proportional to the length of time the control remains effective.

Most of the other benefits of controlling the tailings piles are not quantifiable, although the goals are well defined: the reduction of health risks from exposure to the hazardous materials contained in the tailings. For example, we are unable to translate flood protection measures into the number of health effects averted. The missing linkages are: 1. The translation from specific flood protection measures to flood damage averted; 2. The translation from flood damage to the pile to distribution of tailings spread along the downstream river valley; and 3. The translation from the tailings spread along the river valley to the number, length, and level of exposures. There are similar problems with quantifying the chance of misuse. The permanence of erosion control, i.e., the years of erosional spreading avoided and the years of water quality protection can be evaluated, but, the consequences avoided are not readily quantified.

The benefits for each alternative standard are displayed in Tables 10-1 through 10-3 and are quantified when possible.

The benefits of controlling tailings at existing sites are summarized in Table 10-1. There were about 150 million tons of tailings at 23 active mill sites January 1980. Table 10-1 is presented primarily to show the cost effectiveness of controlling existing tailings, which may be different than the cost effectiveness of controlling future tailings.

The benefits of controlling tailings at all sites, both existing and new, are summarized in Tables 10-2 and 10-3. The benefits are summarized for the baseline projection (see Section 2.6) in Table 10-2 and for the low growth projection in Table 10-3.

10.1.1 Benefits of Stabilization

The benefits of stabilizing the tailings are expressed in terms of the reduced chance of misuse, the permanence of controls for inhibiting misuse, and the years of erosional spreading avoided. The number of health effects averted cannot be estimated.

The major benefit of stabilizing a pile is the prevention of the hazards associated with human intrusion and misuse of the tailings piles; this can be expressed only in qualitative terms. We have estimated, as best we can, the number of years that control is anticipated to inhibit misuse. This ranges from 0 years for the no-requirements standard (A) to 1,000 years for the standards having more stringent requirements (F). The alternatives with thick earth covers are estimated to inhibit misuse for a period of hundreds to thousands of years. Also, the below-grade disposal method, with a 3-meter earth cover up to the original ground contour, is expected to provide greater inhibition of misuse than above-grade disposal with the same cover thickness.

The likelihood of misuse during the period of effectiveness of these alternatives ranges from most likely for the no-requirements alternative to unlikely for alternatives with 3 meters of earth cover and very unlikely for the method with 5 meters of earth cover.

Table 10-1. Benefits of Controlling Uranium Mill Tailings at Existing Active Sites[a]

	Stabilization			Radon Control			Water Protection
		Minimum time			Deaths Avoided		
Alternative Standards	Chance of Misuse	Misuse Inhibited (y)	Erosion Avoided (y)	Residual Risk[b] of Lung Cancer (% reduction)	In first 100 years	Total	Groundwater Protected (y)
A	Very likely	0	0	4 in 10^2 (0)	0	0	0
B	Likely	100	Hundred	2 in 10^2 (50)	200	900	100
C	Less likely	Few 100	Hundreds	1 in 10^2 (80)	350	Thousands	100's
D	Unlikely	1,000	Thousands	2 in 10^3 (95)	400	Many thousands	1,000
E	Unlikely	>1,000	Many thousands	2 in 10^3 (95)	400	Many thousands	>1,000
F	Very unlikely	>1,000	Many thousands	1 in 10^4 (>99)	450	Tens of thousands	>1,000

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[a] For tailings at 23 licensed sites as of January 1980.

[b] Lifetime risk of fatal cancer to an individual assumed to be living 600 meters from center of a tailings pile.

Table 10-2. Benefits of Controlling Uranium Mill Tailings at Active Mill Sites through the Year 2000 for the Baseline Estimate[a]

	Stabilization			Radon Control			Water Protection
		Minimum time			Deaths Avoided		
Alternative Standards	Chance of Misuse	Misuse Inhibited (y)	Erosion Avoided (y)	Residual Risk[b] of Lung Cancer (% reduction)	In first 100 years	Total	Groundwater Protected (y)
A	Very likely	0	0	4 in 10^2 (0)	0	0	0
B	Likely	100	Hundred	2 in 10^2 (50)	700	2,800	100
C	Less likely	Few 100	Hundreds	1 in 10^2 (80)	1,100	Thousands	100's
D	Unlikely	1,000	Thousands	2 in 10^3 (95)	1,400	Many thousands	1,000
E	Unlikely	>1,000	Many thousands	2 in 10^3 (95)	1,400	Many thousands	>1,000
F	Very unlikely	>1,000	Many thousands	1 in 10^4 (>99)	1,400	Tens of thousands	>1,000

[a] These estimates include the benefits resulting from control of 23 existing piles and 51 projected new piles.

[b] Lifetime risk of fatal cancer to an individual assumed to be living 600 meters from center of a tailings pile.

Table 10-3. Benefits of Controlling Uranium Mill Tailings at Active Mill Sites through the Year 2000 for the Low Growth Estimate[a]

	Stabilization			Radon Control			Water Protection
		Minimum time			Deaths Avoided		
Alternative Standards	Chance of Misuse	Misuse Inhibited (y)	Erosion Avoided (y)	Residual Risk[b] of Lung Cancer (% reduction)	In first 100 years	Total	Groundwater Protected (y)
A	Very likely	0	0	4 in 10^2 (0)	0	0	0
B	Likely	100	Hundred	2 in 10^2 (50)	600	2,400	100
C	Less likely	Few 100	Hundreds	1 in 10^2 (80)	1,000	Thousands	100's
D	Unlikely	1,000	Thousands	2 in 10^3 (95)	1,200	Many thousands	1,000
E	Unlikely	>1,000	Many thousands	2 in 10^3 (95)	1,200	Many thousands	>1,000
F	Very unlikely	>1,000	Many thousands	1 in 10^4 (> 99)	1,200	Tens of thousands	>1,000

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[a] These estimates include the benefits resulting from control of 23 existing piles and 40 projected new piles.

[b] Lifetime risk of fatal cancer to an individual assumed to be living 600 meters from center of a tailings pile.

The Grand Junction cleanup program is an example of the kind of expensive remedial actions that stabilization should prevent. The tailings in Grand Junction buildings are now being cleaned up at a costof about $23 million, to avoid an estimated 75 to 150 lung cancer deaths. The additional cost of cleaning up contaminated offsite land is estimated at $22 million to $31 million.

A second benefit of stabilization is the prevention of erosion. The benefit of preventing tailings erosion can be expressed in a semiquantitative way by estimating the number of years that erosional spreading is prevented. Protection from erosion is estimated to range from a few hundred years to many thousands of years for the various alternatives. Since erosion may now be taking place at some sites, benefits can be derived from any remedial measure that reduces erosion.

A third benefit of stabilization is prevention of floods from washing tailings downstream to flood plains, where land use is residential and agricultrual. Should this happen, expensive remedial measures would probably be needed. A recent tailings "spill" (failure of a dam containing a tailings pile at an active mill) in the Southwest contaminated hundreds of acres of land (of limited value) over a distance of about 20 miles. We estimate the cost of cleanup of that spill to be $1 million to $5 million, depending on the cleanup criteria used. The total radioactivity spilled was less than 5 percent of that in an average inactive pile.

10.1.2 Benefits of Radon Control

The estimated benefits of radon control can be quantified. For individuals living near a tailings pile, the benefit is a reduction in health risk. The maximum risk of death to nearby individuals during their lifetime is estimated to be about 4 chances in 100 for the no-requirements of Alternative (A). This risk drops to 2 chance in 100 for Alternative B and to 2 chances in 1,000 for Alternatives D and E. The greatest risk reduction is achieved by Alternative F, which has a 2 pCi/m^2s radon emission limit and reduces the risk to about 2 chances in 10,000.

The total national lung cancer death rate from radon emissions from existing active piles is estimated at 450 per century if no controls are used. This estimate will increase as additional tailings are produced if controls are not used. Alternatives with a 20 pCi/m^2s radon emission rate (D and E) would reduce this rate to about 22 per century for hundreds to thousands of years. The benefit from a more restrictive radon emission rate (F) would be the virtual elimination of the radon risk. Alternative F is estimated to provide greater than 99 percent control of radon for at least 1,000 years.

10.1.3 Benefits of Protecting Water

Protection of water quality is a benefit that cannot be quantified, because future uses of the water cannot be estimated. Unlike air, which must be breathed, water may or may not be used in ways that might cause an increase in health risks. Also, water may be tested for contaminants and, if polluted, it may be cleaned to levels suitable for its projected use, or may be rejected, if an alternative is available. However, after disposal the protective cover, or cap, over the tailings can be quite effective at reducing the volume of liquids entering the tailings and therefore can substantially reduce the potential for contamination of groundwater for long periods.

The benefit of protecting groundwater is the preservation of its existing quality for future uses. These uses are drinking, lifestock watering, and limited irrigation. A specific benefit of groundwater protection would be the reduction, or elimination, of molybdenosis in cattle, which has occurred at a site in Colorado where molybdenum from a tailings pond contaminated groundwater.

Existing uranium tailings are located in areas with low precipitation. This means there is little need to discharge waste water to surface waters. Waste water can be held in ponds, where it evaporates or can be recycled back to the process. Only one uranium mill currently has a National Pollution Discharge Elimination System (NPDES) permit, under the Clean Water Act, for example. However, uranium mining and milling may occur in wetter areas in the future where discharges to surface waters may be unavoidable. In these cases, the operator would be required to obtain a NPDES permit, which would assure protection of surface water quality.

10.2 Benefits and Costs for a Model Tailings Pile

The benefits derived from disposal of tailings have been estimated as shown in Tables 10-1 through 10-3 for the various alternative standards. The total costs of these methods have been estimated as listed in Table 10-4. In this section these benefits and costs are evaluated for each alternative standard.

10.2.1 Alternative Standard A

This alternative is used as a baseline to which the benefits of other methods can be compared. While this alternative would not achieve the goals or objectives of the disposal standards, it has the significant benefit of preventing the flagrant discharge of all tailings into surface waters. This control has been practiced by the industry for some time, however, and is considered appropriate as a baseline.

Table 10-4. Total Costs of Controlling Uranium Tailings at Active Sites
(1981 dollars in millions discounted at 10%)

Alternative Standards	Existing Tailings (as of Jan. 1980)	All Tailings at Active Sites to the Year 2000	
		Baseline Scenario	Low Growth Scenario
A	0	10	6
B	98	337	267
C	115	384	310
D	190	530	440
E	190	549	452
F	334	818	709

10.2.2 Alternative Standard B

The concept underlying this alternative is active control and maintenance. The thin earth cover, loam, and vegetation would reduce radon emanation and associated health effects by about 50 percent for the 100-year period maintenance is performed. This would reduce deaths from radon to about 6 per century from a remote site and 18 per century from a rural site. The total radon deaths avoided would be 2,800 for the baseline projection and 2,400 for the low growth projection from all tailings generated to the year 2000. The chance of misuse is small for 100 years because of a fence and continuing human activities such as maintence and inspection. Annual inspection and repair actions would provide protection against windblown and surface water contamination and external radiation for as long as such actions continue.

The benefits for this alternative are considered to end when maintenance activities cease. Once the sprinkling (irrigation) of the vegetation stops, chemicals from the tailings will probably kill the vegetation, and the thin cover will be denuded and rapidly eroded. However, this scenario could be modified by selection of a site where the deposition of material exceeds the erosion of material. Even in this case the deposition rate is likely to be low, thus allowing continued radon releases and significant chances of misuse for a long period.

The estimated total cost for Alternative B is $337 million for both new and existing tailings sites under the baseline projection and $267 million for the low growth projection.

The estimated number of accidental and radiation induced deaths for Alternative B is 8 for the baseline projection and 6 for the low growth projection.

10.2.3 Alternative Standard C

This alternative would require control of about 80 percent of the radon for most soils. This control reduces the deaths from radon to about 2 per century for a remote site and 8 per century from a rural site. The total radon deaths avoided would be in the thousands for both the baseline and low growth projections. The chance of misuse would be low during an initial period, especially if large size rock is used on the slopes. However, with the passage of time the chance of misuse would increase as reasons to avoid the pile (disposed tailings) were forgotten or became obscure and erosion began to uncover the pile. It is estimated that this initial period would be about 100 years, after which the likelihood of misuse would increase. The benefits of preventing windblown and surface water contamination and protecting against external gamma radiation are estimated to last hundreds of years.

The estimated total cost for Alternative C is $384 million for both new and existing tailings sites under the baseline projection and $310 million for the low growth projection.

The estimated number of accidental and radiation induced deaths for Alternative C is 15 for the baseline projection and 13 for the low growth projection. This includes control of existing tailings plus all tailings generated to the year 2000.

10.2.4 Alternative Standard D

Controls required by this alternative should reduce radon releases by a factor of about 20, using almost any type of soil. This reduction is likely to be greater in most cases since many soils have attenuation properties that would reduce radon releases by a factor of about 100. Using a control factor of 95 percent, the number of radon related deaths would be reduced to about one per century for a remote site and two per century for a rural site. The total radon induced deaths avoided would be in the many thousands for both the baseline and low growth projections.

The significant benefit of this alternative is the substantial reduction in the probability of human intrusion, especially over the long term. A major undertaking would be required to remove significant quantities of tailings. The use of heavy equipment with attendant expenses would probably involve a thorough review of property ownership and tailings characteristics, and approvals by local governments. All this would appear to make it likely that the hazardous nature of the materials would be recognized before they were recovered and used. This "inhibition of misuses" benefit would probably extend for a period of hundreds of years.

The benefits derived from preventing contamination of surface waters and soil surfaces and from reduction of external radiation are estimated to last for 1,000 years.

The estimated total cost for Alternative D is $530 million for both new and existing tailings sites under the baseline projection and $440 million for the low growth projection.

The estimated number of accidental and radiation-induced deaths for Alternative D is 19 for the baseline projection and 16 for the low growth projection. This includes control of all tailings (existing plus future) generated to the year 2000.

10.2.5 Alternative Standard E

This alternative would require staged disposal of the tailings, whereby several tailings storage ponds are used during the lifetime of a mill. After each pond is filled, it is allowed to dry and is then covered with 3 meters of earth. This has the additional benefits over Alternative D of reducing the total quantity of tailings requiring disposal at the end of mill life and of controlling part of the radon emissions during operations. This latter benefit is discusssed in Chapter 7. Staged disposal is considered feasible for new impoundments only. Existing tailings piles, which may contain future tailings, are controlled to levels described in Alternative D.

The benefits of this alternative include reductions in radon deaths that are the same as those under Alternative D, a greatly reduced chance of misuse for hundreds of years, and virtual elimination of surface water and land contamination and external radiation exposure. The chance of misuse is likely to be less for Alternative E than for Alternative D because the tailings disposal site should be indistinguishable from the surrounding terrain. By placing the tailings below grade and covering them to the initial land contour, there would be no easily identifiable pile with rock covered slopes, clearly an indication of human activity.

The estimated total cost for Alternative E is $549 million for both new and existing tailings sites under the baseline projection and $452 million for the low growth projection.

The estimated number of accidental and radiation-induced deaths for Alternative E is 19 for the baseline projection and 16 for the low growth projection.

10.2.6 Alternative Standard F

Alternative F provides greater benefits by specifying a more stringent radon emission rate of 2 pCi/m^{2}s. Thus, radon releases are reduced by greater than 99 percent. This provides a benefit of reducing the total radon related deaths by many thousands. The benefits of inhibiting misuse are also substantially greater than for alternatives specifying a less stringent radon emission rate.

It is expected that this alternative would be met by using thicker earth covers of about 5 meters. The extra thick cover and the long, gradual slopes covered with rock would probably provide protection against misuse for at least 1,000 years.

The benefits of external radiation control and prevention of land and surface water contamination would probably last thousands of years.

The total costs for Alternative F are $818 million for the baseline projection and $709 million for the low growth projection.

This alternative considers the benefits and costs of a very thick cover (5 meters). The estimated number of accidental and radiation-induced deaths is estimated as 22 for the baseline projection and 19 for the low growth projection.

APPENDIX A
(Reserved)

APPENDIX B

ESTIMATED COSTS FOR DISPOSAL OF URANIUM BYPRODUCT MATERIALS

Appendix B: ESTIMATED COSTS FOR DISPOSAL OF URANIUM BYPRODUCT MATERIALS

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Appendix B: ESTIMATED COSTS FOR DISPOSAL OF URANIUM BYPRODUCT MATERIALS

B.1 Characteristics of Model Tailings Piles

The costs for disposal of uranium byproduct materials are estimated in this appendix for alternative disposal standards. The disposal methods, with one exception, use earth covers of various thicknesses which are stabilized with vegetation and rock. We believe this is the most likely method of disposal. The one exception is a tailings solidification method which is described in detail by the Nuclear Regulatory Commission (NRC80).

The costs of liners on the bottoms of tailings impoundments are included for completeness since they represent a significant capital cost. In practice, a liner is an operational control that protects groundwater during the operational phase of a tailings pond. Long-term protection of groundwater is provided by the cover. The estimates are arranged so that costs of liners can be easily subtracted for analysis purposes. Additional cost estimates for protecting groundwater are presented in Chapter 7.

Existing Tailings Piles

In early 1980, there were 23 licensed uranium mills with tailings piles. An analysis of these piles indicated that since they vary widely in size, control costs would also vary greatly. Consequently the piles were grouped into model piles as follows:

a. a 2-million-ton pile on 48 hectare with an average depth of 2.37 meters.

Number of piles in this group = 10
Average tons per pile = 1.8 million
(Range = 1.0 to 2.8 million tons)
Average area covered = 48 hectares
(Range = 13.8 to 98.4 hectares)

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b. a 7-million-ton pile on 56 hectares with an average depth of 7.72 meters

Number of piles in this group = 10
Average tons per pile = 6.85 million
(Range = 4.2 to 11.0 million tons)
Average area covered = 56 hectares
(Range = 31.1 to 86.6 hectares)

c. a 20-million-ton pile on 98 hectares with an average depth of 12.85 meters

Number of piles in this group = 3
Average tons per pile = 19.9 million
(Range = 17.1 to 24.6 million tons)
Average area covered = 98 hectares
(Range = 82.6 to 106.2 hectares)

Separate calculations are needed for each model pile and for each disposal method.

Another important feature of the model piles is the additional area that would be covered by tailings when the sides of the tailings piles, which consist of the sands (coarse fraction), are sloped or contoured to provide additional erosion control. Two values are used for the slopes of the pile edges after grading, 5:1 (H:V) and 8:1 (H:V). The volume of tailings moved is estimated by calculating the volume of the sloped tailings where the vertical distance is the average depth of the pile and the horizontal distance is 5 or 8 times the vertical. The pile is assumed to be square. The amount of additional land covered and the volume of tailings moved by sloping the edges of the piles are:

Pile Size	Additional Land Covered (ha)		Tailings Moved (thousands of cubic meters)	
	5:1 slope	8:1 slope	5:1 slope	8:1 slope
2 million tons	3.3	5.4	39	63
7 million tons	12.3	19.7	459	746
20 million tons	26.6	44.0	1,690	2,760

These values can increase the cost significantly for those methods involving disposal in place. It may be more economical to move the tailings into the center of the pile, thereby forming a hemisphere rather than cover the additonal land area with soil. However, it is not clear that this method would be less costly, since the grading and shaping of such large volumes is also costly.

New Tailings Piles

Information on tailings to be generated at a model new mill are taken from the NRC GEIS (NRC80). The NRC model mill has an ore-processing capacity of 1,800 MT per day. The ore grade is expected to average 0.1 percent uranium, and the uranium recovery efficiency is assumed to be 93 percent. The mill is operated 310 days per year (i.e., 85 percent capacity utilization rate), and the average annual production is 580 MT yellowcake, which is 90 percent U_3O_8. The model pile covers an area of 80 ha with earth embankments around the tailings, bringing the total area to 100 ha. The ultimate depth of the tailings is about 8 meters.

The tailings will be generated at a rate of 1,800 MT per day, or 558 thousand MT per year, or 8.4 million MT during the assumed 15-year operating period of the mill. The tailings are discharged to an impoundment in the base case, which is analyzed later in this appendix as case NT1.

B.2 Tailings Disposal Unit Costs

The most likely methods for disposal of the tailings involve covering the tailings with earth, as discussed in Chapter 8. The unit costs for earth work, transportation, fencing, landscaping, rock cover, and maintenance and inspection are shown in Table B-1. All costs (except rock cover, maintenance, and inspection) were taken from the "Dodge Guide to Public Works and Heavy Construction Costs" (DG81). The unit cost for rock cover is taken from Means (Me82).

Maintenance and inspection costs are calculated for: (1) an irrigaton system for maintaining vegetation on thin earth covers, (2) fencing maintenance, and (3) annual inspections, including groundwater monitoring and repair and revegetation of eroded areas.

Irrigation

The irrigation system design was developed for EPA by PEDCO Environmental, Inc. (PE82). The design is for a 40-acre site (about 16 hectares) and consists of a 150-hp motor and pump unit, polyethylene piping, and plastic spray heads. The capital costs of this system are $127,000, and it is assumed that it must be replaced every 20 years. The present value of capital requirements for 100 years of operation is $149,000, using a 10 percent discount rate and replacement at 20, 40, 60, and 80 years. Annual costs of operation are $12,000 per year for maintenance and labor; $9,300 a year for electrical power; and $6,000 per year for overhead, assuming the system is operated 8 hours per week, 8 months per year. The present value of these annual costs is $273,000 for

Table B-1 Unit Costs
(1981 Dollars)

Task	Cost
Earth work:	
Grading:	
Move and spread by dozer.	$\$1.07/y^3$ ($\$1.40/m^3$)
Placing clay liners and covers:	
Purchase clay, haul 2 miles, dump, spread, and compact.	$\$8.84/y^3$ ($\$11.58/m^3$)
Placing earthern cover:	
Excavate, haul, spread, and compact by scrapers for 3,500 feet.	$\$2.06/y^3$ ($\$2.70/m^3$)
Excavate, load, haul by truck for 2 miles off the highway; dump, spread, and compact.	$\$2.00/y^3$ ($\$2.62/m^3$)
Excavating pits:	
Excavate, haul, and spread, by scrapers, for 3,500 feet.	$\$1.83/y^3$ ($\$2.40/m^3$)
Moving tailings:	
Excavate by drag line. Load, haul 2 miles off highway, spread, and compact.	$\$2.50/y^3$ ($\$3.28/m^3$)
Transportation:	
Over highway hauling of earth, tailings, clay, loam, etc.	$\$0.40/y^3/mile$ ($\$0.52/m^3/mile$; $\$0.33/m^3/km$)
Rock cover:	
18" thick.	$\$13.60/y^2$ ($\$16.27/m^2$)
Landscaping:	
Loam from site used. Preparation of area, spread loam 6 inches thick, and hydraulically spread lime, fertilizer, and seed.	\$3,000/acre (\$7,400/ha)
Loam purchased and hauled 2 miles. Prepare area, spread loam 6 inches thick, and hydraulically spread lime, fertilizer, and seed.	\$7,900/acre (\$19,500/ha)

Table B-1. Unit Costs (Continued)
(1981 Dollars)

Task	Cost
Fencing:	
Chain link, 6 feet high, 6-gauge aluminum.	\$21.60/ft (\$70.87/m)
Maintenance and inspection:	
Installation and operation of an irrigation system for 100 years - present worth at 10% discount rate.	\$10,500/acre (\$26,000/ha)
Maintenance of fencing at 1% of capital cost per year. Present value at 10% discount rate for 100 years.	0.10 x capital cost of fencing
Annual inspections including groundwater monitoring and repair and revegetation of eroded areas. Present value at 10% discount rate for 100 years.	\$95,000/site

100 years using a 10-percent discount rate. Therefore, the total present value of providing irrigation for 100 years is \$422,000 for a 40-acre site, or \$10,500 per acre.

Fencing

Maintaining the fence for 100 years is assumed to cost 1 percent of the installation cost annually. The present value of this maintenance cost for 100 years at 10-percent discount rate is:

Present Value of Fencing Maintenance = 0.10 x fencing capital cost.

Annual Inspections

The cost for annual inspections at a site is taken directly from Appendix R of (NRC80). For this purpose, we used NRC Scenario IV, which requires only limited maintenance. Their inspection costs are \$10,500 annually. This includes \$1,000 per year for maintenance of the fence. Since this cost is already considered, it is subtracted, giving an annual cost of \$9,500 per site. The present value is \$95,000 per site, using a 10 percent discount rate for 100 years.

Borrow Pit Reclamation

The costs for reclaiming borrow pits were estimated for 3 cases: borrow pit in flat terrain; borrow pit on a 10:1 slope; and borrow pit on a hilltop or knoll. For all three cases, stripping and saving 15 centimeters of top soil and revegetation following replacement of the top soil were assumed. The four side walls in the flat terrain pit and the high wall on the 10:1 slope pit were graded to an 8:1 slope before top soil replacement and revegetation. No grading was required for the hilltop case. The hilltop case had the least costs for most methods, and the 10:1 slope case had the greatest costs for all methods. Therefore, to represent an average estimate, the costs for the flat terrain case were used for borrow-pit reclamation. These costs are presented in Table B-2.

B.3 Descriptions of Disposal Methods

Existing Tailings Piles

Method ET1

The edges of the square tailings pile are graded and contoured to a 5:1 (H:V) slope. The entire area is then covered with 0.5 meter of earth obtained nearby. A 6-feet high, 6-gage aluminum chain link fence is placed around the exclusionary zone, which is assumed to be 0.5 kilometer from all sides of the pile. The covered pile is landscaped,assuming that suitable loam or topsoil is available onsite. The borrow-pit reclamation cost is taken from Table B-2. Maintenance and inspection are added for a 100-year period. The costs for this method are summarized in Table B-3.

Method ET2

The sides of the tailings piles are graded to 5:1 (H:V) slope. The tailings are covered with 1 meter of earth obtained nearby and the slopes are covered with 0.5 meter of rock cover. There is no maintenance and inspection of the pile. A fence is installed to form an exclusion area 0.5 kilometer wide all around the disposed tailings. The borrow pit is reclaimed as described in Section B.2. The costs for this method are shown in Table B-4.

Method ET3

For this method the edges of the square tailings pile are graded to a 5:1 (H:V) slope. The entire tailings area is covered with 3 meters of earth obtained nearby or locally. After covering, the slopes are covered with rock, and the tailings are landscaped. No fence is necessary. The borrow pit is reclaimed as described in Section B.2. The costs for this option are listed in Table B-5.

Table B-2. Reclamation Costs for a Borrow Pit on Flat Terrain[a]
(1981 dollars in millions)

Size of Tailings Pile	Cover Thickness on Tailings Pile			
	0.5 meter	1 meter	3 meters	5 meters
2 million tons				
5:1 slope	0.18	0.28	0.69	1.06
8:1 slope	-	0.28	0.73	1.10
7 million tons				
5:1 slope	0.22	0.39	0.95	1.29
8:1 slope	-	0.40	1.05	1.42
20 million tons				
5:1 slope	0.34	0.64	1.42	2.18
8:1 slope	-	0.67	1.59	2.45

---

[a] Where it is assumed that 15 cm of topsoil were stripped and saved, the four side walls of the pit were graded to an 8:1 slope, the top soil was replaced, and the area revegetated. The size and depth of the pit varied, depending on the amount of soil needed to cover the tailings; however, in no case was the borrow pit excavated deeper than 12 meters.

Table B-3. Disposal Cost Summary: Method ET1
(1981 dollars in millions)

	Size of Pile (MT)		
Task	2	7	20
Grading slopes	0.06	0.64	2.37
Excavating, hauling, spreading and compacting cover material	0.69	0.92	1.63
Excavating pit	-	-	-
Placing liner	-	-	-
Excavating, hauling, spreading, and compacting tailings	-	-	-
Fencing	0.49	0.52	0.60
Landscaping	0.38	0.50	0.92
Placing rock cover	-	-	-
Reclaiming borrow pit	0.18	0.22	0.34
Maintain for 100 years	1.47	1.91	3.39
Contingency, overhead and profit	0.65	0.94	1.85
TOTAL	3.92	5.65	11.10
Composite Unit Costs:			
\$/MT Tailings	1.96	0.81	0.56
\$/MT U_3O_8	2,107	868	597

Method ET4

The sides of the tailings piles are graded to a 8:1 (H:V) slope, after which the entire area is covered to a 3-meter depth with earth obtained nearby or locally. The slopes are covered with 0.5 meter rock cover, and the earth-covered tailings are landscaped. No fence is needed. The borrow pit is reclaimed as described in Section B.2. The costs for this option are presented in Table B-6.

Method ET5

The edges of the tailings piles are contoured to a slope of 8:1 (H:V). The entire area is then covered with 5 meters of earth obtained nearby. The slopes are covered with a 0.5-meter thick rock cover, and the earth-covered tailings are landscaped. No fence is necessary. The borrow pit is reclaimed as described in Section B.2. The costs for this option are presented in Table B-7.

Method ET6

The sides of the tailings piles are graded to a 5:1 (H:V) slope. The entire area is then covered with 1 meter of earth obtained nearby, after which a 0.5-meter rock cover is added to the entire area. A fence is installed to form an exclusion area 0.5 kilometer wide all around the disposed tailings. The borrow pit is reclaimed as described in Section B.2. The costs for this method are listed in Table B-8.

Method ET7

This disposal method provides for below surface level disposal of the tailings, with a 3-meter earth cover over the tailings and a 1-meter clay liner below the tailings. For the 2-million-ton pile, a 366-meter square pit is excavated to a 12-meter depth adjacent to the pile. The bottom of the pit is assumed to be above the groundwater table. The pit is lined with 1 meter of purchased clay hauled 3.2 kilometers. The tailings are moved into the pit with scrapers, after which they are covered with 3 meters of the excavated earth. The disposal area is landscaped. The area covered by excess excavated earth is restored.

The disposal pit for the 7-million ton pile is 614 meters square by 15 meters deep, and the pit for the 20-million-ton pile is 1,047 meters square by 15 meters deep. Both pits are assumed to be above the groundwater table. Because of the large sizes, hauling by trucks for an average off-road distance of 3.2 kilometers is assumed. The disposal method and landscaping are similar to those of the 2-million ton-case. The costs for this method are summarized in Table B-9.

Table B-4. Disposal Cost Summary: Method ET2
(1981 dollars in millions)

Task	Size of Pile (MT) 2	7	20
Grading Slopes	0.06	0.64	2.37
Excavating, hauling, spreading and compacting cover material	1.38	1.84	3.26
Excavating pit	-	-	-
Placing liner	-	-	-
Excavating, hauling, spreading, and compacting tailings	-	-	-
Fencing	0.54	0.57	0.66
Landscaping	0.36	0.41	0.73
Placing rock cover	0.54	1.95	4.32
Reclaiming borrow pit	0.28	0.39	0.64
Contingency, overhead and profit	0.63	1.16	2.40
TOTAL	3.79	6.96	14.38
Composite Unit Costs $/MT Tailings	1.90	0.99	0.72
$/MT U_3O_8	2,037	1,069	773

Table B-5. Disposal Cost Summary: Method ET3
(1981 dollars in millions)

Task	Size of Pile (MT) 2	7	20
Grading slopes	0.06	0.64	2.37
Excavating, hauling, spreading and compacting cover material	4.15	5.51	9.79
Excavating pit	-	-	-
Placing liner	-	-	-
Excavating, hauling, spreading, and compacting tailings	-	-	-
Fencing	-	-	-
Landscaping	0.36	0.41	0.73
Placing rock cover	0.54	1.95	4.32
Reclaiming borrow pit	0.69	0.95	1.42
Contingency, overhead and profit	1.16	1.89	3.72
TOTAL	6.94	11.35	22.34
Composite Unit Costs:			
$/MT Tailings	3.47	1.62	1.12
$/MT U_3O_8	3,730	1,743	1,201

Table B-6. Disposal Cost Summary: Method ET4
(1981 dollars in millions)

Task	Size of Pile (MT) 2	7	20
Grading slopes	0.09	1.04	3.80
Excavating, hauling, spreading, and compacting cover material	4.29	5.90	11.08
Excavating pit	-	-	-
Placing liner	-	-	-
Excavating, hauling, spreading, and compacting tailings	-	-	-
Fencing	-	-	-
Landscaping	0.36	0.41	0.73
Placing rock cover	0.88	3.20	7.15
Reclaiming borrow pit	0.73	1.05	1.59
Contingency, overhead and profit	1.27	2.32	4.87
TOTALS	7.62	13.92	29.22
Composite Unit Costs:			
$/MT Tailings	3.81	1.99	1.46
$/MT U_3O_8	4,096	2,138	1,571

Table B-7. Disposal Cost Summary: Method ET5
(1981 dollars in millions)

Task	Size of Pile (MT)		
	2	7	20
Grading slopes	0.09	1.04	3.84
Excavating, hauling, spreading, and compacting cover material	6.94	9.84	18.46
Excavating pit	-	-	-
Placing liner	-	-	-
Excavating, hauling, spreading, and compacting tailings	-	-	-
Fencing	-	-	-
Landscaping	0.94	1.09	1.91
Placing rock cover	0.88	3.20	7.15
Reclaiming borrow pit	1.10	1.42	2.45
Contingency, overhead and profit	1.99	3.32	6.76
TOTALS	11.94	19.91	40.57
Composite Unit Costs:			
$/MT Tailings	5.97	2.84	2.03
$/MT U_3O_8	6,418	3,058	2,186

New Tailings Piles

Method NT1

This method is the same as the base case in the NRC analysis (NRC80). An initial square basin would be formed by building low earthen embankments along each side of 947 meters length at the centerline. The mill tailings would be slurried into the basin, and as the basin filled, the coarse fraction of the tailings (sands) would be used to raise and broaden the embankments. The final dimensions of the embankments would be 10 meters high and 13 meters wide at the top. When the mill ceases operations, no specific control measures for disposal would be used. The cost for this option is listed in Table B-10 and consists only of preparation of the initial basin.

Method NT2

This method is similar to ET1, since both use a thin earth cover on the tailings and rely on institutional controls to prevent misuse. A pit is excavated close to the mill and measures 930 meters square by 2 meters deep. Embankments are constructed along each side, 947 meters long, 10 meters high, and 13 meters wide at the top. The pit is lined with 1 meter of clay obtained locally. Tailings are pumped directly into the pit during operation of the mill. It is assumed that water from the pond will be recycled to the mill, thereby negating the need for an evaporation pond.

At the end of mill life, the embankments are excavated and placed on top of the tailings to a depth of 0.5 meter. The slopes of the covered tailings are graded to 5:1 (H:V). The entire area is landscaped. A fence is placed around the disposal area and provides a 0.5-kilometer exclusion zone. The site is maintained for 100 years by irrigation of the vegetative cover and inspection and repair of the earth cover and fence. Costs are shown in Table B-10.

Method NT3

This method is similar to ET2, since both use a 1-meter earth cover and a 0.5-meter rock cover on the slopes. A pit is prepared and used in the same manner to that described for method NT2.

At the end of mill life, the embankments are excavated and placed on top of the tailings to a depth of 1 meter. The slopes of the disposed tailings are graded to 5:1 (H:V) and then covered with rock to a depth of 0.5 meter. The top of the disposed tailings area (that part not covered with rock) is landscaped. A fence is contructed at a distance of 0.5 kilometer from the edge of the disposed tailings all around the site. The costs are listed in Table B-10.

Method NT4

This method is similar to ET3, since both use a 3-meter earth cover and a 0.5-meter rock cover on the slopes. A pit is excavated, prepared, and used in the same manner as that described for method NT2.

At the end of mill life, the embankments are excavated and placed on top of the tailings. Additional earth cover is obtained from a nearby borrow pit so that the final earth cover over the tailings is 3 meters deep. The slopes of the covered tailings are graded to 5:1 (H:V) and are covered with a 0.5-meter rock cover. The top of the earth-covered tailings is landscaped. The borrow pit is reclaimed. The costs are listed in Table B-10.

Method NT5

This method is somewhat similar to the staged or phased disposal method described by the NRC's GEIS (NRC80). This method uses 6 pits, each 300 meters square and 13 meters deep. Two pits are constructed initially and lined with 1 meter of clay. Tailings are pumped to the first pit until it is full and then pumped to the second pit. When the first pit is sufficiently dry, the third or fourth pit is excavated, and the excavated earth is used to cover the first pit to a depth of 3 meters up to the original ground contour. This process continues sequentially until the end of mill life. An evaporation pond is needed in this method. Costs for this pond are taken from the NRC GEIS and corrected for inflation.

At the end of mill life there will likely be four completed pits, which are covered with 3 meters of earth to the original ground contour and 2 uncovered pits. When sufficiently dry, these last two pits are covered with 3 meters of excavated earth to the original ground contour. The disposed tailings area is landscaped. The areas covered by the evaporation pond and excess excavated earth are restored. The costs for this method are presented in Table B-10.

Method NT6

This method is the same as Alternative 7 in the NRC GEIS (NRC80). The tailings are pumped to the edge of a depleted mine pit, where the sands (coarse fraction) and slimes (fine fraction) are separated. The sands are washed, dried, and deposited in the mine pit. The slimes are partially dried, mixed with cement, and deposited in the mine pit where the cement and fine slurry would harden. The cost for this method is listed in Table B-10.

Method NT7

This method is similar to ET5, since both use a 5-meter earth cover and a 0.5-meter rock cover on the slopes. A pit is excavated, prepared, and used in the same manner as that described for method NT2.

At the end of mill life, the embankments are excavated and placed on top of the tailings. Additional earth cover is obtained from a nearby borrow pit so that the final earth cover over the tailings is 5 meters deep. The slopes of the covered tailings are graded to 8:1 (H:V) and are covered with a 0.5-meter rock cover. The top of the earth-covered tailings is landscaped. The borrow pit is reclaimed. The costs are listed in Table B-10.

Table B-8. Disposal Cost Summary: Method ET6
(1981 dollars in millions)

Task	Size of Pile (MT) 2	7	20
Grading slopes	0.05	0.64	2.35
Excavating, hauling, spreading, and compacting cover material	1.37	1.82	3.24
Excavating pit	-	-	-
Placing liner	-	-	-
Excavating, hauling, spreading, and compacting tailings	-	-	-
Fencing	0.54	0.57	0.66
Landscaping	-	-	-
Placing rock cover	8.34	11.05	20.25
Reclaiming borrow pit	0.35	0.39	0.64
Contingency, overhead and profit	2.14	2.90	5.40
TOTALS	12.79	17.37	32.54
Composite Unit Costs:			
\$/MT Tailings	6.40	2.48	1.63
\$/MT U_3O_8	6,875	2,668	1,749

Table B-9. Disposal Cost Summary: Method ET7
(1981 dollars in millions)

Task	Size of Pile (MT) 2	7	20
Grading slopes			
Excavating, hauling, spreading, and compacting cover material	1.08	2.94	8.55
Excavating pit	3.82	14.70	42.75
Placing liner	1.55	4.37	12.69
Excavating, hauling, spreading, and compacting tailings	3.70	14.09	40.97
Fencing	-	-	-
Landscaping	0.10	0.28	0.81
Placing rock cover	-	-	-
Reclaiming borrow pit	-	-	-
Contingency, overhead and profit	2.06	7.28	21.20
TOTAL	12.31	43.66	126.92
Composite Unit Costs:			
\$/MT Tailings	6.16	6.24	6.35
\$/MT U_3O_8	6,617	6,705	6,822

Table B-10. Disposal Cost Summary: Methods NT1 Through NT6
(1981 dollars in millions)

Task	Disposal Method (For 8.4-Million-Ton Pile) NT1	NT2	NT3	NT4	NT5	NT6	NT7
Excavate pit and construct embankments	0.96	4.67	4.67	4.67	18.61[a]	-	4.67
Placing liner	-	10.00	10.00	10.00	7.38	-	10.00
Grading slopes	-	1.34	1.34	1.34	-	-	2.14
Spreading and compacting cover material	-	1.17	2.33	7.00	-	-	11.70
Fencing	-	0.58	0.64	-	-	-	-
Landscaping	-	0.67	0.67	0.67	0.40	-	0.67
Placing rock cover	-	-	3.16	3.16	-	-	5.00
Reclaiming borrow pit	-	-	-	1.08	-	-	2.45
Maintain for 100 years	-	3.03	-	-	-	-	-
Other costs	-	-	-	-	3.48	75.97	-
Contingency, overhead, and profit	0.19	4.30	4.56	5.58	5.97	15.19	7.32
TOTAL	1.15	25.76	27.37	33.50	35.84	91.16	43.92
Composite Unit Costs:							
\$/MT Tailings	0.14	3.07	3.26	3.99	4.27	10.85	5.23
\$/MT U_3O_8	147	3,297	3,503	4,287	4,587	11,666	5,622

[a] Includes covering pits.

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APPENDIX C

HEALTH BASIS FOR HAZARD ASSESSMENT

Appendix C: HEALTH BASIS FOR HAZARD ASSESSMENT

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Appendix C: HEALTH BASIS FOR HAZARD ASSESSMENT

Introduction

Inhalation or ingestion of radionuclides or toxic chemicals can have adverse effects on human and animal health. The adverse effects can be separated, generally, into stochastic and nonstochastic. Stochastic effects are those in which the probability of the effect is proportional to the exposure level, but the severity of the effect is independent of exposure. Nonstochastic effects are those in which the severity of the effect is proportional to the exposure level and there is usually a threshold level of exposure below which no effect is observed.

Low levels of radiation exposure, such as that associated with inhalation or ingestion of radionuclides transported into the environment from tailings piles, generally produce stochastic effects. Radiation from radionuclide particles deposited on the ground may also expose people causing stochastic effects. Ingestion or inhalation of toxic chemicals from tailings piles would cause nonstochastic effects.

For purposes of this analysis, only stochastic effects (e.g., cancer and inherited abnormalities) will be considered in the case of ionizing radiation exposure and only nonstochastic (e.g., acute and chronic poisoning) in the case of exposure to toxic elements.

C.1 Risk Models for Stochastic Effects

There are two kinds of risks from the low levels of ionizing radiation characteristic of exposures to radionuclides released into the environment. The most important of these is cancer, which is fatal at least half the time. The other risk is the induction of hereditary effects in descendants of exposed persons; the severity ranges from fatal to inconsequential. As mentioned above, we assume that at low levels of exposure the risk of cancer and hereditary effects is in proportion to the dose received, and that the severity of any induced effect is independent of the dose level. That is, while the probability of a given type of cancer occurring increases with dose, such a cancer induced at one dose is equally as debilitating as that same type of cancer induced at another dose. For these effects, we assume that there is no completely risk-free level of radiation exposure.

The risks and effects on health from low-level ionizing radiation were reviewed for EPA by the National Academy of Sciences in reports published in 1972 and in 1980 (NAS72a, NAS80b). We have used these studies and others to estimate the risks associated with the radiation doses calculated in this report.

The individual lifetime risk can be estimated for the "most exposed individuals;" these people are located at the point of highest lifetime risk. The risk to the individual is the risk of premature death from cancer due to the radiation dose received. The risk calculation considers all important radionuclides, pathways, and organs of the body.

The risk to an individual can be subdivided and related to other parameters. For example, we can determine which part of the risk is committed by radionuclides moving through a specific pathway or which organ is at highest risk. This information is helpful when deciding which control strategies will be the most effective.

The risk to populations can also be estimated; that is, the number of future effects on health that are committed for each year that the source operates. The risks are associated with doses delivered to people over a time period which is longer than the average individual's lifespan. The dose is not necessarily delivered to people during the years of release because radionuclides with long half-lives may take a long time to move through environmental pathways to people.

Like the individual lifetime risk, the total risk to populations can be subdivided and related to other parameters, such as organ, radionuclide, or exposure pathway.

The genetic risk is the risk to future generations associated with the dose equivalent to the gonads of both exposed parents over the first 30 years of their lives. We calculate the total genetic risk for the same population for which we calculate the collective potential fatal cancer risk.

C.1.1 The RADRISK Code

The estimates of cancer and genetic risk are calculated using a computer code called RADRISK. In RADRISK, the group assumed to be at risk by the code is a hypothetical cohort of 100,000 people, all born simultaneously and subject to the same risks throughout their lives. Each member is assumed to be exposed at a constant rate to a unit concentration of radionuclides. For each radionuclide and for each pathway, the code calculates the number of premature deaths due to radiation and the number of years of life lost due to these deaths.

When radionuclides are inhaled, they enter the lung, and the ICRP Task Group lung model is used to predict where in the lung they go and

Table C-1. Risk parameters for cancers considered (Su81)

Cancer	Latency (years)	Plateau (years)	Risk Factor		Number of premature deaths in cohort from chronic 1 mrad/y exposure*
			Low-LET radiation (deaths/10^6 rad person-years at risk)	High-LET radiation (deaths/10^6 rad person-years at risk)	
Leukemia	2	25	2.3	46	0.326
Bone	5	30	0.2	4	0.031
Lung	10	110	3.0	30	0.608
Breast	15	110	2.3	2.3	0.399
Liver	15	110	0.9	9	0.154
Stomach	15	110	0.5	5	0.087
Pancreas	15	110	0.7	7	0.121
Lower Large Intestine	15	110	0.4	4	0.069
Kidneys	15	110	0.2	2	0.035
Bladder	15	110	0.2	2	0.035
Upper Large Intestine	15	110	0.2	2	0.035
Small Intestine	15	110	0.1	1	0.017
Ovaries	15	110	0.1	1	0.017
Testes	15	110	0.1	1	0.017
Spleen	15	110	0.1	1	0.017
Uterus	15	110	0.1	1	0.017
Thymus	15	110	0.1	1	0.017
Thyroid	2	45	0.4**	0.4**	0.085

*Low-LET

**0.04 for ^{131}I and longer-lived radioiodine.

how fast they are removed to other parts of the body. Depending on size and solubility class, there is removal of some of this material to the gastrointestinal (GI) tract and absorption by the blood. A GI tract model is used to estimate how much of the material reaching the tract is absorbed by the blood.

After absorption by the blood, radionuclides are distributed among the organs according to uptake and metabolic information supplied to RADRISK. Dose rates are calculated with the help of models that simulate the biological processes involved when radionuclides enter and leave organs.

Cancers do not appear immediately after exposure. There is a latent period before the cancers are observed; the length, usually years, varies with the type of cancer. Thereafter, there is a specified period when there is a finite probability of cancer, a "plateau" period, and it also varies with the type of cancer. Table C-1 lists the risk parameters used in RADRISK.

Lifetime probabilities for many types of cancer, in many organs, are followed and risks calculated. At the same time, competing risks unrelated to the radiation exposure are accounted for. The RADRISK code does this; however, we do not yet understand how accurate these calculations are. In particular, cancer risks and metabolic parameters are uncertain, and since relative risk estimates are not available for all radiation-induced cancers, only an absolute risk estimate is made. We believe risks are accurate to an order of magnitude only and should never be reported to more than one significant figure.

Inherited abnormalities (genetic effects), as noted above, do not occur in those exposed to radiation but in their progeny. The genetic risk coefficient used in RADRISK is:

Table C-2. Genetic Risk Parameters

	First Generation	All Generations
Risks per one million live-births per mrad low-LET radiation	0.04	0.2

A more detailed description of RADRISK can be found in ORNL/TM-7745, "Estimates of Health Risk from Exposure to Radioactive Pollutants" (Su81).

C.2 Risk Estimates for Inhaled Radon and Radon-Daughters (Radon Decay Products)

An estimate of the health risk from inhaling radon and its short-lived daughters has been done separately for both historic and technical reasons.

The history of the health impact of exposure to radon and its short-lived daughters has its roots in the past, before the discovery of x-rays or identification of radioactivity. The units of exposure, Working Level (WL), Working Level Month (WLM), are unusual and do not fit into the RADRISK computer code. The risk of radon, radon-daughter exposure has been calculated independently of the RADRISK program calculations for this analysis.

C.2.1 Risk of Lung Cancer from Inhaling Radon Decay Products

The high incidence of lung cancer mortality among underground miners is well documented (EPA79a, Ar79, Ar81). Uranium miners are particularly affected, but lead, iron, and zinc miners exposed to relatively low levels of radon decay products also show an increased lung cancer mortality that correlates with exposure to radon decay products. The type of lung cancer most frequently observed, moreover, is relatively uncommon in the general population.

Risk estimates for the general public based on these studies of miners are far from precise. First, and most important, the relatively small number of miners at risk injects considerable statistical uncertainty into estimating the number of excess lung cancer cases (see Figure C-1). Second, although the cumulative lifetime exposure in contaminated buildings can be comparable to that of some miners, most of the miners studied were exposed to much higher levels of radon decay products than usually occur in the general environment. Third, the exposure levels are uncertain. Fourth, significant demographic differences exist between miners and members of the general public--the miners were healthy males over 14 years old, many of whom smoked. However, information from the studies of miners can provide useful estimates, if not precise predictions, of the risks to the general population from radon decay products.(1)

Since the miners being studied have not all died, their eventual excess lung cancers must be projected from current data by using mathematical models. There are two ways to use the observed frequency of lung cancer deaths among the exposed miners to estimate the risk from inhaling radon decay products over a person's lifetime. One,

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(1) See "Indoor Radiation Exposure Due to Radium-226 in Florida Phosphate Lands" (EPA 79a) for greater detail of such an analysis.

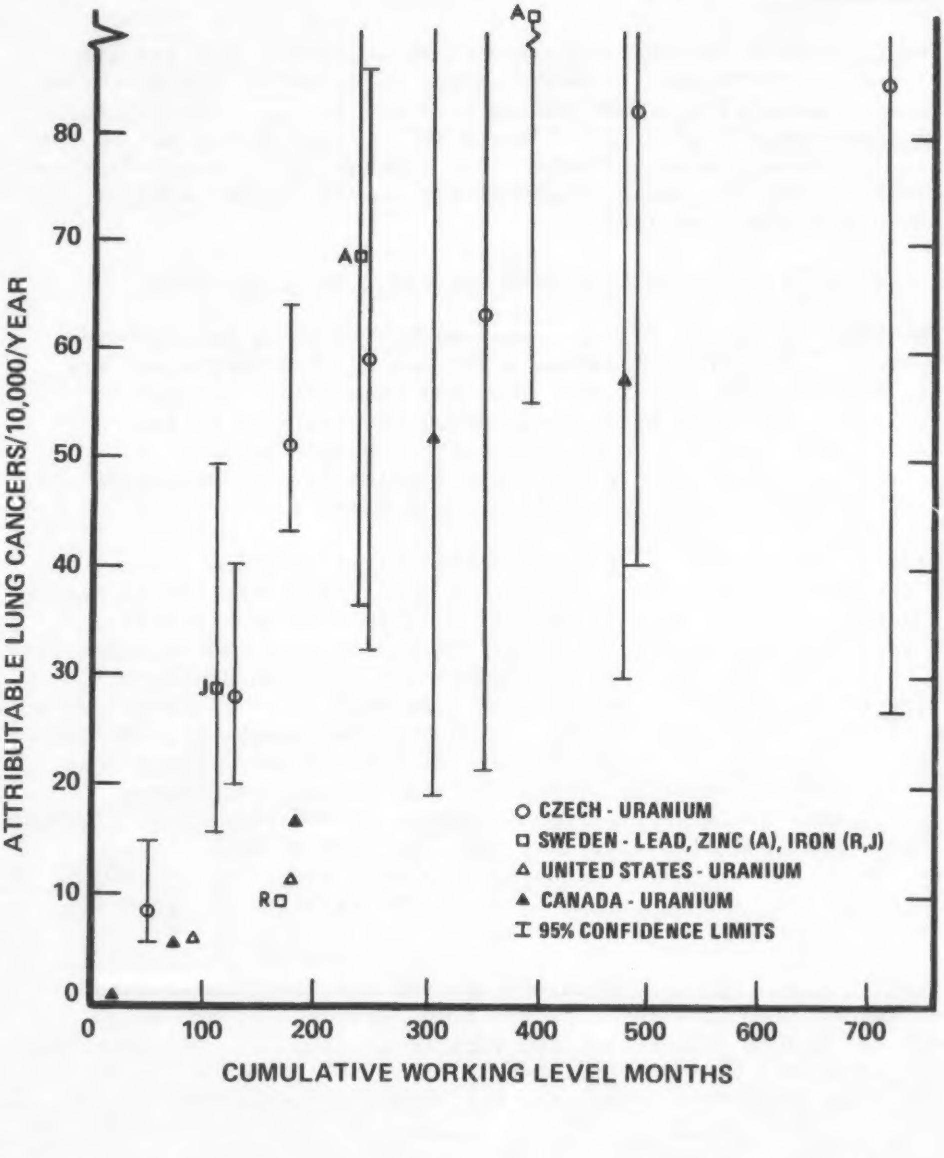

Figure C-1. EXCESS FATAL LUNG CANCER IN VARIOUS MINER GROUPS BY CUMULATIVE EXPOSURE (Ar79).

commonly called the relative risk model, yields the percent increase in the normal incidence of cancer per unit of exposure. The other, called the absolute risk model, yields the absolute numerical increase in cancers per unit of exposure. In the relative risk model, it is assumed that the increased risk is proportional to the age-dependent natural incidence of the disease for each year an individual remains alive following exposure. In the absolute risk model, it is assumed that the added risk is independent of natural incidence, i.e., the risk is constant each year an individual remains alive following exposure.

As a basis for calculating estimates using the relative risk model, we conclude that a 3-percent increase in the number of lung cancer deaths per WLM is consistent with data from the studies of underground miners. However, because of the differences between adult male miners and the general population (EPA79a), we estimate that the risk to the general population may be as low as 1 percent or as high as 5 percent. To develop absolute risk estimates in earlier reports, we used the estimate of 10 lung cancer deaths per WLM for 1 million person-years at risk reported by the National Academy of sciences (NAS76). In a 1978 paper, Land and Norman (La78) reported that in Japanese A-bomb survivors, radiation-induced lung cancers had a temporal distribution of occurrence similar to naturally-occurring cancers of the same site. Further, they concluded the cumulative distribution of radiation-induced lung cancer across time after exposure was consistant with a relative risk model of cancer incidence or with an age-specific absolute risk model.

In a paper at the same symposium, Smith and Doll (Sm78) reported the risk of cancer developing at most "heavily irradiated" sites in ankylosing spondylitic patients treated with x-rays was directly proportional to the risk of a tumor in the absence of radiation; in other words, a relative-risk-like response. In the most recent report on the Japanese A-bomb survivors, Kato and Schull (Ka82) reiterated the observation that radiation-induced lung cancer develops only after the survivors attain the age at which this cancer normally develops. The evidence in these three reports of external radiation exposure points to relative-risk or age-specific absolute risk models as being appropriate for radiation-induced lung cancer.

Recent information from China provides similar evidence for exposure to radon, radon daughters. Shi-quan and Xiao-ou (Sh82) have reported that in Chinese tin miners exposed to radon and its daughters, the lung cancers developed at the age at which lung cancer normally develops. Those who started mining at age 8 or 9 had an induction-latent period about 10 years longer than those who started mining at age 19 or 20. Here, again, a simple absolute risk model will not fit the observations.

In view of these observations that a simple absolute risk model is inappropriate for estimating the risk of lung cancer due to radon daughter exposure, a simple absolute risk estimate was not calculated. A prior comparison of risks calculated using a relative model and the age-specific absolute risk model from BEIR III (NAS80b) showed them to be numerically similar (860 cases/10^6 person-WLM versus 850 cases/10^6 person-WLM) (RPC80). Because of the similarly in risk estimates, only relative risk estimates for radon daughter exposures are used in this document.

Unless we state otherwise, we estimate excess cancer fatalities, i.e., those caused by elevated radiation levels that are in addition to those from other causes.

To estimate the total number of lung cancer deaths from increased levels of radon in the environment, we have used a life-table analysis of the additional risk due to radiation exposure (Bu81). This analysis uses the risk coefficients just discussed. It also takes into account the length of time a person is exposed and the number of years a person survives other potential causes of death based on 1970 U.S. death rate statistics. The result is expressed as the number of premature lung cancer deaths that would occur due to lifetime radiation exposure of 100,000 persons. We assume, further, that injury caused by alpha radiation is not repairable, so that exposed persons remain at risk for the balance of their lifetimes.

Using the relative risk model, we estimate that a person exposed to 0.01 WL (.27 WLM/y) over a lifetime incurs a 1.7 percent (1 in 60) additional chance of contracting a fatal lung cancer. This estimate was made assuming children are no more sensitive than adults. If exposure to radon decay products during childhood carries a three times greater risk, this estimated lifetime relative risk would increase by about 50 percent (EPA79a). Using a similar lifetable analysis and an absolute risk model, we would have estimated that a person exposed to 0.01 WL over a lifetime incurs a 0.7 percent (1 in 140) additional chance of contracting a fatal lung cancer. Again, equal child and adult sensitivities are assumed (EPA79a). For comparison, a lifetable analysis for the same population not exposed to excess radiation yields a 2.9 percent chance of lung cancer death.

Even though, under either of these models, the risk of radon-induced lung cancer varies with age, it is sometimes convenient to express these risks on an average annual basis. We have calculated a person's average annual risk from a lifetime of exposure by dividing the lifetime risk estimates given above by an average lifespan of 71 years.(1) Based on the risk model and assumptions just described for lifetime exposure, we estimate an average of 2.4 lung cancer deaths per year for each 100 person-working-levels of such exposure. "Person-working-levels" is the population's collective exposure; that is, the number of people times the average concentration of radon decay products (in working levels) to which they are exposed.

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(1) Note that this is not the same as applying the risk coefficient for 71 years, since the lifetable analysis accounts for other causes of death.

For the entire U.S. population, the estimated number of cancers is large using the relative risk model, but this estimate does not hold for all locations because the lung cancer rate varies considerably in different parts of the country. Therefore, we can base our relative risk estimate for each source on the lung cancer death rate for the State in which the source is located. Lung cancer death rates are lower than the national average in several of the States, so at some localities the relative risk is lower than at others.

Radiation risk can also be stated in terms of years of life lost due to cancer death. In the relative risk model, the distribution of ages at which lung cancer caused by radiation occurs is the same as that for all lung cancer in the general population. Since lung cancer occurs most frequently in people over 70 years of age, the years of life lost per fatal lung cancer--14.5 years on the average--is less than for many other fatal cancers. The absolute risk model wrongly assumes that lung cancer fatalities occur at a uniform rate throughout life and, therefore, each fatality reduces the lifespan by a larger amount--an average of 24.6 years.

Because we used recent population data, our assessments are for current conditions. If the population lifestyle, medical knowledge, and other patterns of living affecting mortality remain unchanged, then these rates of lung cancer death could persist for the indefinite future. We have not attempted to assess the effects of future change, which may either increase or decrease our risk estimates. It is prudent, we believe, to assume that estimated risks based on current data could persist over the indefinite future.

C.3 Risk Factors per Unit Exposure

Risk factors computed in the RADRISK program or in the radon risk program for unit exposure are listed in Tables C-2 through C-9.

C.4 Risks From Toxic Materials, Nonstochastic Effects

Toxic materials have been considered in this analysis if they are in substantially greater concentration in the source than in native rocks or soils or in a relatively mobile form (anionic or cationic). Materials that are harmful to livestock and plants as well as those potentially affecting humans directly have been included. Evaluating the potential risks from nonradioactive toxic substances requires

Table C-3. Lifetime Risk of Excess Cancer in a Cohort of 100,000 from Continuous Exposure to ^{210}Pb

	Inhalation (1 pCi/y)				
	Particle Size				
Organ	0.3 μm	7.75 μm	54.2 μm	Ingestion (1 pCi/y)	Ground Deposition (1 pCi/cm^2)
Red Marrow	3.6E-4	4.1E-4	3.9E-4	1.3E-4	1.3E-3
Endosteum	1.8E-4	2.1E-4	2.0E-5	6.4E-4	1.4E-4
Pulmonary Lung	2.0E-6	3.8E-7	1.8E-7	3.6E-8	1.0E-3
Breast	4.5E-6	5.0E-6	4.9E-6	1.6E-6	9.1E-4
Liver	3.4E-4	3.9E-4	3.8E-4	1.2E-4	2.0E-4
Stomach Wall	7.3E-9	1.4E-8	1.4E-8	1.6E-8	1.3E-4
Pancreas	1.0E-5	1.1E-5	1.1E-5	3.6E-6	1.1E-4
Lower Large Intestine Wall	6.8E-8	5.3E-7	6.0E-7	1.2E-6	5.6E-5
Kidneys	3.8E-5	4.1E-5	3.9E-5	1.3E-5	4.9E-5
Bladder Wall	1.5E-6	1.6E-6	1.6E-6	5.0E-7	3.5E-5
Upper Large Intestine Wall	1.0E-8	5.9E-8	6.6E-8	1.3E-7	3.5E-5
Small Intestine Wall	2.1E-9	5.1E-9	5.5E-9	7.8E-9	1.5E-5
Ovaries	1.5E-6	1.6E-6	1.6E-6	5.1E-7	3.0E-5
Testes	1.5E-6	1.6E-6	1.6E-6	5.1E-7	4.6E-5
Spleen	1.7E-6	1.6E-6	1.5E-6	4.9E-7	2.1E-5
Uterus	1.5E-6	1.6E-6	1.6E-6	5.1E-7	6.4E-6
Thymus	1.5E-6	1.6E-6	1.6E-6	5.1E-7	2.5E-5
Thyroid	1.0E-6	1.2E-6	1.1E-6	3.6E-7	2.0E-4
TOTAL	9.5E-4	1.1E-3	1.0E-3	3.4E-4	4.3E-3

Table C-4. Lifetime Risk of Excess Cancer in a Cohort of 100,000 from Continuous Exposure to Polonium-210

	Inhalation (1 pCi/y) Particle Size				
Organ	0.3 µm	7.75 µm	54.2 µm	Ingestion (1 pCi/y)	Ground Deposition (1 pCi/cm^2)
Red Marrow	2.6E-4	3.8E-4	3.6E-4	1.8E-4	3.1E-6
Endosteum	5.6E-6	8.1E-6	7.6E-6	3.8E-6	3.1E-7
Pulmonary Lung	4.1E-2	5.9E-3	1.4E-3	7.0E-12	5.1E-6
Breast	1.6E-5	2.3E-5	2.1E-5	1.0E-5	3.6E-6
Liver	1.9E-4	2.7E-4	2.6E-4	1.3E-4	1.2E-6
Stomach Wall	8.2E-8	1.6E-7	1.7E-7	2.0E-7	6.9E-7
Pancreas	4.8E-5	6.9E-5	6.5E-5	3.2E-5	9.1E-7
Lower Large Intestine Wall	2.6E-6	5.2E-6	5.5E-6	6.2E-6	4.1E-7
Kidneys	2.4E-4	3.5E-4	3.3E-4	1.6E-4	2.9E-7
Bladder Wall	6.8E-6	9.8E-6	9.2E-6	4.6E-6	2.7E-7
Upper Large Intestine Wall	4.3E-7	8.6E-7	9.2E-7	1.0E-6	2.7E-7
Small Intestine Wall	3.7E-8	7.3E-8	7.8E-8	8.8E-8	1.2E-7
Ovaries	6.8E-6	9.8E-6	9.2E-6	4.6E-6	8.0E-8
Testes	6.8E-6	9.8E-6	9.2E-6	4.6E-6	1.5E-7
Spleen	2.1E-4	3.0E-4	2.4E-4	1.4E-4	1.6E-7
Uterus	6.8E-6	9.8E-6	9.2E-6	4.6E-6	1.1E-7
Thymus	6.8E-6	9.8E-6	9.2E-6	4.6E-6	1.0E-7
Thyroid	3.3E-6	4.8E-6	4.5E-6	2.2E-6	5.6E-7
TOTAL	4.2E-2	7.4E-3	2.8E-4	6.9E-4	1.7E-5

Table C-5. Lifetime Risk of Excess Cancer in a Cohort of 100,000 from Continuous Exposure to Radium-226

Organ	Inhalation (1 pCi/y) Particle Size		Ingestion (1 pCi/y)	Ground Deposition (1 pCi/cm^2)
	7.75 μm	54.2 μm		
Red Marrow	8.9E-4	8.6E-4	5.9E-4	3.9E-3
Endosteum	3.6E-4	3.4E-4	2.4E-4	4.0E-4
Pulmonary Lung	7.2E-3	1.8E-3	7.0E-7	4.5E-3
Breast	1.7E-5	1.6E-5	1.1E-5	3.0E-3
Liver	5.8E-5	5.6E-5	3.8E-5	1.0E-3
Stomach Wall	2.6E-7	2.6E-7	2.5E-7	4.8E-4
Pancreas	4.8E-5	4.6E-5	3.2E-5	5.9E-4
Lower Large Intestine Wall	1.1E-5	1.2E-5	1.3E-5	3.2E-4
Kidneys	1.3E-5	1.2E-5	8.5E-6	2.1E-4
Bladder Wall	6.9E-6	6.6E-6	4.5E-6	1.9E-4
Upper Large Intestine Wall	1.3E-6	1.3E-6	1.5E-6	2.1E-4
Small Intestine Wall	1.1E-7	1.1E-7	1.1E-7	1.0E-4
Ovaries	6.9E-6	6.6E-6	4.5E-6	7.6E-5
Testes	6.9E-6	6.6E-6	4.5E-6	1.8E-4
Spleen	6.4E-6	6.2E-6	4.2E-6	1.1E-4
Uterus	6.9E-6	6.6E-6	4.5E-6	8.1E-5
Thymus	6.9E-6	6.6E-6	4.5E-6	1.1E-4
Thyroid	3.6E-6	3.4E-6	2.3E-6	7.1E-4
TOTAL	8.7E-3	3.1E-3	9.6E-4	1.6E-2

Table C-6. Lifetime Risk of Excess Cancer in a Cohort of 100,000 from Continuous Exposure to ^{230}Th

	Inhalation (1 pCi/y) Particle Size		Ingestion	Ground Deposition
Organ	7.75 μm	54.2 μm	(1 pCi/y)	(1 pCi/cm^2)
Red Marrow	2.3E-2	1.5E-2	2.4E-4	2.9E-4
Endosteum	1.6E-2	1.1E-2	1.7E-4	3.0E-5
Pulmonary Lung	6.6E-2	1.6E-2	3.7E-10	2.7E-4
Breast	8.0E-6	5.2E-6	8.4E-8	2.5E-4
Liver	1.5E-4	9.7E-5	1.6E-6	5.3E-5
Stomach Wall	1.7E-7	1.8E-7	1.8E-7	3.1E-5
Pancreas	2.4E-5	1.6E-5	2.5E-7	3.3E-5
Lower Large Intestine Wall	6.0E-6	6.2E-6	6.3E-6	1.9E-5
Kidneys	6.9E-6	4.5E-6	7.3E-8	1.2E-5
Bladder Wall	3.5E-6	2.3E-6	3.6E-8	9.9E-6
Upper Large Intestine Wall	1.0E-6	1.0E-6	1.0E-6	1.0E-5
Small Intestine Wall	8.5E-8	8.8E-8	8.9E-8	4.9E-6
Ovaries	3.5E-6	2.3E-6	3.6E-8	4.7E-6
Testes	3.5E-6	2.3E-6	3.6E-8	1.3E-5
Spleen	3.5E-6	2.3E-6	3.6E-8	5.7E-6
Uterus	3.5E-6	2.3E-6	3.6E-8	3.0E-6
Thymus	3.5E-6	2.3E-6	3.6E-8	5.4E-6
Thyroid	1.8E-6	1.1E-6	1.8E-8	4.6E-5
TOTAL	1.1E-1	4.2E-2	4.2E-4	1.1E-3

Table C-7. Lifetime Risk of Excess Cancer in a Cohort of 100,000 from Continuous Exposure to ^{234}U

Organ	Inhalation (1 pCi/y) Particle Size		Ingestion (1 pCi/y)	Ground Deposition (1 pCi/cm^2)
	7.75 μm	54.2 μm		
Red Marrow	2.4E-5	1.6E-5	2.3E-4	1.4E-4
Endosteum	1.6E-5	1.1E-5	1.5E-4	1.5E-5
Pulmonary Lung	6.7E-2	1.6E-2	1.7E-6	1.1E-4
Breast	1.3E-7	8.4E-8	1.2E-6	1.9E-4
Liver	4.7E-7	3.2E-7	4.5E-6	1.6E-5
Stomach Wall	2.0E-7	2.0E-7	4.2E-7	1.3E-5
Pancreas	3.6E-7	2.5E-7	3.5E-6	1.4E-5
Lower Large Intestine Wall	6.1E-6	6.3E-6	5.3E-6	1.0E-5
Kidneys	1.1E-5	7.5E-6	1.1E-4	3.4E-6
Bladder Wall	5.7E-8	3.9E-8	5.5E-7	2.8E-6
Upper Large Intestine Wall	1.0E-6	1.1E-6	9.5E-7	2.8E-6
Small Intestine Wall	9.1E-8	9.2E-8	1.2E-7	1.4E-6
Ovaries	5.2E-8	3.6E-8	5.0E-7	1.9E-6
Testes	5.2E-8	3.6E-8	5.0E-7	9.6E-6
Spleen	5.2E-8	3.6E-8	5.0E-7	1.9E-6
Uterus	5.2E-8	3.6E-8	5.0E-7	7.6E-7
Thymus	5.2E-8	3.6E-8	5.0E-7	1.6E-6
Thyroid	2.7E-8	1.8E-8	2.5E-7	1.6E-5
TOTAL	6.7E-2	1.6E-2	5.1E-4	5.4E-4

Table C-8. Lifetime Risk of Excess Cancer in a Cohort of 100,000 from Continuous Exposure to ^{238}U

	Inhalation (1 pCi/y) Particle Size		Ingestion	Ground Deposition
Organ	7.75 μm	54.2 μm	(1 pCi/y)	(1 pCi/cm^2)
Red Marrow	2.0E-5	1.4E-5	1.9E-4	7.6E-5
Endosteum	1.3E-5	9.0E-6	1.3E-4	8.3E-6
Pulmonary Lung	6.1E-2	1.5E-2	1.5E-6	5.2E-5
Breast	2.7E-7	1.2E-7	1.2E-6	1.3E-4
Liver	5.1E-7	3.0E-7	3.9E-6	4.6E-6
Stomach Wall	2.9E-7	2.1E-7	3.7E-7	6.3E-6
Pancreas	3.8E-7	2.4E-7	3.2E-6	7.0E-6
Lower Large Intestine Wall	9.2E-6	7.0E-6	5.1E-6	5.8E-6
Kidneys	9.8E-6	6.7E-6	9.5E-5	1.0E-6
Bladder Wall	5.4E-8	3.6E-8	4.9E-7	7.4E-7
Upper Large Intestine Wall	1.5E-6	1.1E-6	8.7E-7	7.9E-7
Small Intestine Wall	1.3E-7	9.6E-8	1.1E-7	3.6E-7
Ovaries	4.8E-8	3.1E-8	4.3E-7	9.2E-7
Testes	4.7E-8	3.1E-8	4.3E-7	6.8E-6
Spleen	5.4E-8	3.4E-8	4.5E-7	8.0E-7
Uterus	5.0E-8	3.3E-8	4.5E-7	1.3E-7
Thymus	5.9E-8	3.5E-8	4.5E-7	5.3E-7
Thyroid	5.6E-8	2.6E-8	2.7E-7	6.0E-6
TOTAL	6.1E-2	1.5E-2	4.3E-4	3.1E-4

Table C-9. 30-Year Genetic Dose Commitment
(mrad)

Organ	Lead-210	Polonium-210	Radium-226	Radium-230	Thorium-234	Uranium-238
INHALATION						
(7.75 m particle size)						
Ovary						
Low-LET	9.6E-5	1.6E-9	7.1E-5	2.0E-6	1.8E-7	6.7E-6
High-LET	2.5E-4	1.7E-3	1.2E-3	5.8E-4	8.8E-6	7.3R-6
Testis						
Low-LET	9.4E-5	5.9E-10	3.9E-5	1.8E-6	2.4E-8	5.0E-6
High-LET	2.5E-4	1.7E-3	1.2E-3	5.8E-4	8.8E-6	7.4E-6
(54.2 m particle size)						
Ovary						
Low-LET	9.3E-5	1.6E-9	7.1E-5	1.4E-6	1.8E-7	2.6E-6
High-LET	2.4E-4	1.6E-3	1.2E-3	3.8E-4	6.0E-6	5.1E-6
Testis						
Low-LET	9.1E-5	5.6E-10	3.7E-5	1.2E-6	1.7E-8	1.9E-6
High-LET	2.4E-4	1.6E-3	1.1E-3	3.8E-4	6.0E-6	5.1E-6
INGESTION						
Ovary						
Low-LET	3.1E-5	1.3E-9	6.2E-5	2.0E-7	3.7E-5	1.5E-5
High-LET	7.8E-5	7.8E-4	7.6-6	6.2E-5	8.6E-5	7.2E-5
Testis						
Low-LET	2.9E-5	3.2E-10	2.7E-5	2.4E-8	2.2E-7	1.4E-5
High-LET	7.8E-5	7.8E-4	7.1E-4	6.2E-6	8.6E-5	7.2E-5
GROUND DEPOSITION						
Ovary	4.0E-2	1.4E-4	1.3E-1	8.1E-3	3.2E-3	1.6E-3
Testis	7.9E-2	2.6E-4	3.1E-1	2.3E-2	1.7E-2	1.2E-2

different methods from those used for radioactive substances.(1) As noted earlier, with nonradioactive toxic materials, the type of effect varies with the material; the severity of the effect--but not its probability of occurring--increases with the dose. Moreover, because the body can detoxify some materials or repair the effects small doses, often no toxic effects occur below a threshold dose.

We cannot construct a numerical risk assessment for nonradioactive toxic substances because we do not have enough information. We can, however, qualitatively describe risks of toxic substances in terms of their likelihood of reaching people (or animals, or agricultural products), concentrations at which they may be harmful, and their toxic effects. No acute effects--death in minutes or hours--are expected at concentrations addressed in this analysis. Severe sickness, or death within days to weeks, from the use of highly contaminated water is possible, but unlikely.

Chronic toxicity from the continuous consumption of contaminants at low concentrations could be a problem. Toxic substances can accumulate slowly in tissues, causing symptoms only after some minimum amount has accumulated. Such symptoms of chronic toxicity develop slowly, over months or years.

An extensive section in the EIS for inactive sites (EPA82-83) was devoted to toxicity of elements found in uranium mill tailings and tailings ponds and problems associated with them. Only an abreviated discussion will be presented here. For the more detailed discussion, the EIS for remedial action at inactive sites should be consulted.

At active uranium milling sites, inorganic toxic elements are expected to be the major cause of concern (see Table C-10).

Organic chemicals used in processing ore are recycled and only fugitive releases to tailings ponds might occur. The principal organics associated with uranium milling are kerosene, di (2-ethylhexyl) phosphoric acid (EHPA), tributyl phosphate, tertiary amines (e.g., almine-336) and isodecanol (NRC80).

Although the organic chemicals used in uranium milling are not expected to be released with mill tailings to any appreciable extent, background levels in surface and ground water should be established for both inorganic and organic potential pollutants. Both inorganic chemicals and some organic chemicals may be transported long distances so local levels in water may reflect distant industrial sources of pollution rather than mill operations.

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(1)Many nonradioactive substances can induce cancer in experimental animals (Go77, Ve78). However, for nonradioactive substances found in uranium mill tailings, we do not feel that dose-response relationships adequate for estimating such risks for oral intake have been developed.

Table C-10. Selected Potentially Toxic Substances Associated with Uranium Mill Tailings

Arsenic
Barium
Boron
Cadmium
Chromium
Copper
Cyanide
Iron
Lead
Manganese
Mercury
Molybdenum
Nickel
Nitrates
Radium
Selenium
Silver
Thorium
Uranium
Vanadium

C.4.1. Estimates of Chronic Toxicity in Humans

Data reviewed by the National Academy of Sciences showed that for elements essential to human nutrition, there is a margin of safety between the amount required for good nutritiion and the amount which is toxic. The margin of safety may be narrow; e.g., 10 times the daily recommended intake of arsenic is toxic; or wide, e.g., 1,000 times the daily recommended intake of chromium is toxic (NAS80a). Table C-11 lists selected substances found in uranium mill tailings and estimated toxic levels. Note that these estimates are derived from a number of sources of data and are not adjusted for chemical form of the element, age or sex of subject, or any other factors. The estimates should be viewed as very broad estimates of where toxicity might be expected.

C.4.2 Estimates of Chronic Toxicity in Animals and Plants

Although there is potential for causing acute toxic conditions to develop in plants or animals if tailings pond water or other highly contaminated standing water is used for plants or animals, this is considered unlikely to occur. Induction of chronic toxicity in plants or animals by using contaminated surface water, or more likely, contaminated groundwater is deemed more plausible.

Maintaining water quality no worse than levels specified in the interim primary (EPA76) or secondary (EPA79b) drinking water regulations would also protect plants and animals in most cases. However, these limits may not be adequate to protect dairy cattle, and not all possible contaminants would be covered. Likewise, not all elements potentially toxic to plants would be covered. For a more extended discussion of elements toxic to plants and animals, the National Academy of Sciences 1972 publication, "Water Quality Criteria," (NAS72b) can be consulted.

Table C-11. Daily Intake Levels of Selected Elements Estimated to be Toxic (NAS80a, EPA82)

Element	Ratio of Toxic Intake to Adult Required Intake	Potentially Toxic Intake in Humans (mg)	
		Acute	Chronic
Arsenic	10	23(a)	0.2-0.5
Barium	NE	550-600(a)	?
Boron	NE	15000-30000(a)	?
Cadmium	NE	15-30	0.6
Chromium	1000	?	5-200
Copper	40-135	175-200(a)	80-400
Cyanide	NE	50-200(a)	10
Iron	340-1700	70,000+ (a)	3000-30000
Lead	NE	?	0.1-3
Manganese	120	?	300-600
Mercury	NE	10-200(a)	0.3-3
Molybdenum	10-40	?	2-20
Nickel	112	250	6
Nitrates	NE	8400-42000(a)	10
Radium	NE	?	?
Selenium	100	?	5-20
Silver	NE	140(a)	0.1
Thorium	NE	?	?
Uranium	NE	350(a)	0.6
Vanadium	40-280	1700-17000(a)	1-3

NE - Not reported to be essential in humans.
(a)Deaths are expected.

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APPENDIX D

WATER MANAGEMENT AT URANIUM ORE PROCESSING SITES

APPENDIX D: WATER MANAGEMENT AT URANIUM ORE PROCESSING SITES

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APPENDIX D: WATER MANAGEMENT AT URANIUM ORE PROCESSING SITES

Summary

Operating uranium mills produce effluents containing radioactivity and toxic materials which are potential contaminants to groundwater. Large amounts of tailings effluents placed in unlined evaporation ponds on permeable soil at existing mill sites have seeped into the sandstone bedrock that contains groundwater. Investigations of the altered bedrock along the seepage pathways show attenuation of most of the radionuclides and some of the toxic elements during the neutralization phase of the leachate. Some of the highly mobile and soluble heavy metals, (Mo, V, Mn, Pb, As, and Se) have migrated beyond the neutralization zone into the groundwater. The presence of diagnostic chemical species related to seepage plumes and higher-than-normal concentrations of toxic materials above groundwater background levels disclose the presence of tailings contaminants in the groundwaters close to the uranium mills.

The characteristics of seepage migration are site specific and controlled by the relatively complex hydrogeology of the typical uranium mill site. No satisfactory method exists to abate or predict contaminant movement from these unlined tailings ponds.

Using synthetic liners, clay liners, or a combination of both in the tailings pond seems to be the most effective method of confining mill tailings effluents.. The type of liner used is usually determined by the nature of the waste and conditions of the site. Both clay and synthetic liners are similar in cost. Synthetic liners are more impervious but are subject to tear or puncture. Clay liners, properly designed with structural integrity, can provide an even tighter seal by the precipitation of solids into pore spaces as a result of neutralization reactions attending the interaction of acid waste water and the liner materials.

D.1 Introduction

The water used in the recovery of uranium ore at operating mills contains toxic materials that must be effectively managed to prevent potential surface water or groundwater contamination. It has been

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estimated that as much as 85 percent of the mill tailings effluents are lost to groundwater during the mill's operation (Ja79). Thus, confining water during the mill operating phase is critical in controlling the amount of contaminants available for potential pollution.

Mill tailings effluents discharged to unlined evaporation ponds have resulted in seepage loss of some of the contaminants to groundwater during the operation phase of the mills. Tailings pond seepage has been detected in the groundwater at a number of sites. The maximum distance of migration reported at one site was 1.5 miles (UI80). Within a few years after the mill closes, tailings ponds will evaporate in the arid to semi-arid climate of western United States; this leaves a tailings pile vulnerable to wind and water erosion.

Over the past several years, there have been a number of core hole borings and water monitoring investigations to better understand and develop methods to mitigate the migration from uranium tailings impoundments. These site-specific studies on the extent and travel rates of seepage plumes have identified the radionuclides and toxic material attenuated by the geologic media and have contributed to the understanding of the physicochemical factors involved. The task remains to mitigate the migration of highly mobile contaminants that pollute the groundwater. Emphasis presently is placed on the confinement and retention of effluents in the tailings ponds by synthetic liners, clay liners, or a combination of both; however, some natural media may be impervious to seepage. Future technology directed toward changing the chemistry of tailings pond effluents may help contain the mobile toxic materials that contaminate groundwater.

D.2 Uranium Recovery Processes

There are two basic conventional processes for recovering uranium from the ore: the acid-leach process and the alkaline-leach process. The acid-leach process is used when the ore contains less than 12 percent limestone and generally accounts for 80 percent of the uranium recovery. The alkaline-leach process is used on the remaining 20 percent of the ore milled. Both processes involve an initial dry crushing and grinding, then water is introduced as the ore is wet ground to a pulp density of 50 to 65 percent solids. Water consumption at this step is reduced by recirculating the water.

A leaching process removes the uranium from the crushed ore, with sulfuric acid as the leaching agent in the acid-leach process; a mixed sodium carbonate-sodium bicarbonate solution is the leaching agent in the alkaline-leach process (NRC80a). After ore leaching is completed, the "pregnant" leach liquor containing the dissolved uranium is removed from the tailings solids by a counter current decantation (CCD) circuit. The leach solution is sent to a solvent extraction for further processing, and the remaining solids are washed and pumped as a slurry to the tailings ponds. Water in the tailings ponds generally is characterized by total dissolved solids in the range of 12,000 to 90,000 mg/L with an abundance of dissolved radionuclides and heavy metals. The pH of the water averages about 1.8 for mills using the acid-leach process and about 10.2 for mills that use the alkaline-leach process.

The acid-leach and alkaline-leach processes have considerable chemical differences. A larger fraction of thorium is solubilized in the acid-leach process, but the thorium is precipitated in the tailings pond when the acidity is reduced. In addition to variations in the chemical composition from the milling process used, other variations exist from differences in the composition of the ores related to their origin.

D.3 Contaminants in Uranium Waste

The waste from the milling operations of uranium ore contains all the toxic contaminants present in the original ore, about 10 percent of the uranium not recovered in the process, and a variety of chemicals used in the extraction process. The nature of the contaminants vary in relation to the source of the ore and the type of process used. Radionuclides reported include uranium, thorium, and radium, and toxic materials include arsenic, lead, molybdenum, and selenium. Other elements and parameters reported include iron, manganese, sulfate, chloride, total dissolved substances (TDS), and acidity index (pH). Many levels of toxic materials are more than two orders of magnitude above EPA drinking water standards. Additional heavy metals and chemicals existing in uranium mill wastewater which are locally important, include Sb, Be, Cd, Cr, Cu, Ni, Zn, V, Mn, Al, and ammonia.

The solid portion of the tailings is comprised of particles ranging in size from coarse sands to fine slimes. Quartz and feldspar comprise the major portion of the sands, while fines contain appreciable amounts of clay minerals, gypsum, calcite, and barite in addition to quartz and feldspar (Dr81). In both the acid process and the alkaline process, the residual uranium and radium content of slimes (fines) is about twice that of sands; this is undoubtedly due to the greater concentration of sorptive minerals, e.g., clay minerals, in the slimes. In the acid-leach process, about 95 percent of the thorium in the original ore remains in the solid tailings waste. Less than one percent of the radium is dissolved in the liquids. Even more of the thorium and radium remains in the solid waste from the alkaline-leach process.

Radon gas is released as a daughter radionuclide from the decay of radium-226, which is largely retained in the solid waste. Because radon is chemically inert, it migrates by diffusion from the tailings pile to the atmosphere. Radon emissions rates have been calculated at between 200 to 900 pCi/m^{2}s. Uncontaminated soils average about 1 pCi/m^{2}s by comparison. Standing water and entrapped water in the tailings pile inhibit the release of radon gas so that calculated release rates cited may be high.

D.4 Water Use and Retention at Operating Mills

Water conservation is a necessity in the mining and milling operations of most uranium mills. Mine waters are treated to recover uranium and/or to remove radium, heavy metals, and suspended solids. The treated mine waters are used at the mill as feed water or discharged to the watershed. Currently, only the Uravan, Colorado, mill discharges treated waters as surface water. Water used in the mill is cycled to an impoundment along with the tailings for disposal by evaporation and/or treatment and discharge. Water solution decanted from the ponds in the impoundment system may be recycled to the mill, decreasing fresh water usage. When mines are dry or too far from the mill to permit use of groundwater infiltration into the mine, the mill derives water from wells or, in rarer instances, from surface streams.

The quantity of water used in milling is variable and depends on the process used and the degree of recycling. The acid-leach process requires greater amounts of fresh water than mills using the alkaline-leach process. Fresh water is usually required in acid leach mills for ore grinding, leaching (as steam), counter current decantation washing, and precipitation (Ja79). The alkaline-leach process normally employs a mixed sodium carbonate-sodium bicarbonate leach solution in the grinding circuit with fresh water used for post-leaching filtration and second-stage precipitation (Ja79). The waste streams from the milling process are partially or totally segregated for disposal, especially if recycling from the impoundment system is practiced. Segregation and disposal in separate ponds allow reuse of less contaminated wastes while providing for containment of liquid wastes which contain high concentrations of contaminants.

D.5 Design of Tailings Impoundments

The predominant method of disposal of all solid and liquid wastes generated in the uranium mill today is impoundment of the wastes in a tailings retention system. This system consists of an earthen dam or embankment and an evaporation basin or pond behind the dam. The dam is built in the best location for effluent control. The evaporation basin on the upstream side of the dam is lined with a clay blanket to prevent seepage loss to the underlying soil. As much natural runoff as possible is diverted from the evaporation basin by siting the impoundment to minimize the upstream catchment area or in the construction of ditches to direct the water around the impoundment.

The NRC has issued Regulatory Guide 3.11, "Design, Construction, and Inspection of Embankment Retention Systems for Uranium Mills" which provides the design goals for tailings impoundments (NRC77). The design takes into consideration the protection of the embankment retention systems from the Probable Maximum Flood (PMF). The PMF is defined as the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the region (NRC77). The regulatory guide lists appropriate guidance for determining the Probable Maximum Flood. Methods for estimating return intervals of paleofloods in the particular acute semiarid regions have been described by Kochel and Baker (Ko82).

D.6 Clay and Synthetic Liners

In the early days of uranium milling, not much attention was given to the protection of the subsurface hydrogeologic environment. Most of the mill wastes generated before 1977 are stored in unlined tailings ponds, and some of these have leaked. Most waste disposal sites are located in hydrogeologic environments that consist of nonindurated and/or indurated sediments that were deposited in fluvial environments. Buried river deposits are coarse grained and difficult to detect because of their braided, band-like occurrence in such terrain. High seepage rates of migrating solutions can take place if such formations occur beneath an unlined uranium mill tailings evaporation pond.

Since groundwater monitoring was initiated in 1977, seepage from tailings ponds has been detected in groundwater from a number of sites, with migration as much as 1.5 miles at one of the sites (UI80). The seepage plumes were traced by one or more of several chemical parameters found in the seepage water, particularly sulfate and total dissolved solids. In some cases, this monitoring effort has identified contamination problems which require the use of recovery wells to return contaminated water from seepage plumes back to lined tailings ponds. (UI80).

The technology of pond liners is a relatively recent development. Generally speaking, synthetic liners are used for evaporation ponds of mine waters or less contaminated effluents, and thicker clay liners are used in tailings ponds. Synthetic liners of polyvinyl chloride (PVC), chlorinated polyethylene (CPE), and hypalon (synthetic rubber) used at uranium mills are less permeable (10^{-10} cm/s) than clay liners, but costs are generally higher (Ja79). Synthetic liners, however, are subject to loss of seal by puncture or tearing during installation and are probably less suited to withstand the long-term effects of the chemical environment.

Clay liners, in addition to having structural stability, are effective in sealing ponds because of their layered structure and their high sorptive properties. The desorption of Na^+ from montmorillonite in the mill tailings of the Grants Mineral Belt has been described as being desirable because pollutants are probably being adsorbed in their place on this clay mineral (Lo82). Leaching of clay into liner pores (caused by precipitation) can also increase the impermeability of the clay liner; this enhances the long-term stability of the clay liners (Pe82). Natural clays treated with polymeric materials have also been shown to improve the sealing properties of clay, and permeabilities as small as 10^{-6} to 10^{-8} cm/s have been achieved (Ja79).

The uncertainty of maintaining an acceptable level of environmental control with unlined tailings ponds warrants the use of clay liners or other acceptable liners that meet the licensing requirements. The need for properly constructed clay liners is thus a major cost consideration in constructing new uranium mills.

D.7 Groundwater Monitoring Results

D.7.1 Introduction

Before 1977 most mill wastes were stored in unlined tailings ponds. Seepage from these ponds has contaminated groundwater. The characteristics of seepage movement are site specific, and a number of methods can identify the pathways and extent of pollution to groundwater. Some of the data that were collected at uranium mill disposal sites are incomplete, and some were collected by methods that are not state of the art. The most reliable method of characterizing groundwater contamination is by identifying the chemicals in tailings ponds that are also in groundwater above background levels.

The methods used to delineate the migration path of the seepage plume and the actual groundwater monitoring results at the active mill tailings sites are reviewed in the next section.

D.7.2 Composition of Tailings Ponds

The dissolved radionuclides of primary concern within most tailings ponds include radium-226, thorium-230, uranium-238, lead-210, and polonium-210. Heavy metals found in varying quantities among the uranium mill sites include molybdenum, arsenic, selenium, lead, iron, chromium, manganese, magnesium, cobalt, nickel, barium, vanadium, and copper. Toxic heavy metals are higher in concentration in acid mill waste than in alkaline mill waste. Anions of toxic heavy metals are generally more soluble and, thus, potentially more hazardous than the cationic species of the same element which can be precipitated with lime or sulfide. Major anions formed by heavy metals in tailings ponds include species of arsenic, chromium, molybdenum, uranium, and vanadium. Inorganic anions, notably sulfate, nitrate, and chloride, are present in significant quantities in acid leach mill wastes. Other inorganic anions found in minor amounts in most wastewater include sulfide, cyanide, fluoride, and total dissolved solids (Ja79). Light elements in tailings ponds include potassium, sodium, aluminum, beryllium, calcium, magnesium, and titanium.

While organics are widely used in the extraction process, most of these chemicals are removed, and quantities of organic compounds in mill liquid wastes are low. Typical concentrations of total organic carbon in acid mill waste range from 6 to 24 mg/L in acid mill waste and 1 to 450 mg/L in alkaline mill waste; oil and grease is generally 1 mg/L in acid mill waste and 3 mg/L in alkaline mill waste; MBAS surfactants average 0.5 mg/L in acid mill waste and 0.02 mg/L in alkaline mill waste; phenol is less than 0.2 mg/L for both types of wastes (Ja79). The pH of the waters in the tailings ponds averages about 1.8 for mills using the acid-leach process and about 10.2 for mills using the alkaline extraction process.

D.7.3 The Neutralization Zone

The acid seepage plumes are normally neutralized by carbonate minerals in the bedrock within a few hundred yards of most tailings ponds. At a distance of a few hundred yards, the total dissolved substances can be expected to range from 5,000 to 10,000 mg/L, as contrasted to the 25,000-35,000 mg/L found in normal tailings pond water (UI80). The pH change gradually increases to that of the normal groundwater, and minerals are precipitated that are not generally native to the bedrock in this same distance of transport.

Several investigators have attempted to characterize the transition zone between the mill tailings pond water and the point where it becomes indistinguishable from native groundwater. A recent investigation describes the interaction between the seepage from the tailings ponds and the natural soils by thermodynamic principles; this interaction is based on minerals identified as precipitates and dissolved minerals (Ma82). Gypsum precipitation, for example, results when calcite comes in contact with sulfuric acid; carbon dioxide gas is produced and the calcium reacts with the sulfate to produce gypsum. Barium will also precipitate as $BaSO_4$ and in the process remove radium from solution (Ma82). Conclusions drawn, however, are almost entirely on solid-phase data, and the liquid-phase chemistry is ignored.

Another line of investigation utilizes an analytical hydrogeochemical model based upon acid consumption-neutralization front movement. In this model it is possible to identify and characterize zones within migrating plumes of tailings-derived water by the chemical characteristics of the water (Sh82). An investigation of the seepage from an unlined mill tailings pond in the Wyoming Gas Hills district describes radionuclide retention within the first 40 to 60 cm beneath the pond. The neutralization zone to an 11-meter depth is delineated by typical gypsum precipitation and carbonate removal and increases to the 8.2 pH background level (Er82).

The foregoing investigations describe the retention of certain radioactive and toxic materials attending the neutralization of mill pond seepage and the nature of transition zones. Of major concern is determining what portion of the seepage has gone beyond the neutralization zone to become part of groundwater contamination. This is best determined by groundwater monitoring.

D.7.4 Monitoring Groundwater Contamination

Several groundwater monitoring investigations of uranium mill sites have disclosed chemical pollutants above background levels that are attributed to seepage from unlined mill tailings ponds. A description of these site-specific monitoring findings follows.

Canon City, Colorado

Before 1979, the Cotter Corporation near Canon City, Colorado, used the alkaline-leach process and disposed of mill tailings wastes in a series of unlined tailings ponds. The seepage waste is typical of both the alkaline and acidic types and is described as concentrated sodium sulfate waters with high levels of molybdenum, selenium, and emitters of radiation (UI80).

Concentrations of molybdenum at levels of 16.7 mg/L at a well approximately 8000 feet from the Cotter tailings pond, within an isoconcentration delineated zone, are evidence of pollution from a point source in the tailings pond. The maximum background level of molybdenum in the vicinity of the mill is 1.1 mg/L, and the Drinking Water Standard for molybdenum is 0.05 mg/L (UI80).

A Soil Conservation Reservoir near the tailings pond (3000 feet) has elevated levels of sodium, sulfate, radionuclides, and selenium (in addition to elevated levels of molybdenum) which appear to be related to the seepage effluents from the pond. The complex nature of the hydrogeology around the Cotter Mill, however, makes migration pathways difficult to interpret for engineering corrective measures.

Ford, Washington

The Dawn Mining Company mill near Ford, Washington, has acid-leach process effluent seepage from existing unlined tailings ponds that has contaminated the groundwater beneath the site. Sulfate is the primary tracer of the contamination plume that is easily traced through the highly permeable sand and gravel glacial sediments to an underlying glacial lake, derived clay stratum. At the impervious clay stratum, a groundwater mound gradient is created that causes discharge in a direction approximately 0.5 miles west of the tailings pond to a nearby surface stream (UI80). Uranium concentration in the seepage emergence zone is 0.06 mg/L, whereas uranium in springs not affected by the tailings pond is 0.004 mg/L. However, the only contaminant in the seepage emergence zone that exceeds Drinking Water Standards is nitrate, which occurs in levels of 35 mg/L and is three and one-half times the maximum permissible concentration specified. Sulfate, manganese, and total dissolved solids occur in excess of "recommended" limits for drinking water. Pump-back systems are being considered as engineering control measures to control the pollution.

Gas Hills, Wyoming

The Union Carbide Gas Hills, Wyoming, uranium mill near Riverton, Wyoming, has contributed groundwater contaminants from an unlined tailings disposal pond containing acid-leach process effluents. Water quality in the water-bearing horizons of the Wind River Formation used as background indicator wells barely exceeds the Drinking Water Standards for total dissolved solids, sulfate, selenium, and radium-226 (UI80).

Monitoring wells around the mill tailings pond indicate that migration of contaminants is occurring in the upper alluvial layer and middle sandy layer of the Wind River Formation which has a thickness of 400 feet.

Typical water contamination from a monitoring well to a depth of 140 feet and at a distance of 700 feet from the disposal pond indicate the following: sulfate 2932 mg/L, with 250 mg/L the irrigation standard; selenium 0.26 mg/L, with 0.01 mg/L the irrigation standard; total dissolved solids 5760, with 250 mg/L the irrigation standard; nitrate 150 mg/L, with 10 mg/L the irrigation standard; aluminum 59 mg/L, with 20 mg/L the irrigation standard; manganese 7 mg/L, with 0.05 mg/L the irrigation standard; chloride 893 mg/L, with 250 mg/L the irrigation standard (NRC80b). More monitoring wells would be required to determine how far the seepage has migrated because of the complex hydrogeologic conditions and the interpretation of data required.

Jefferson City, Wyoming

Groundwater has been contaminated by the acid-leach effluent seepage from the Western Nuclear, Inc., Split Rock uranium mill near Jefferson City, Wyoming. The unlined tailings pond leaked contaminants into the underlying Split Rock Formation comprised of fine-grained sandstone having a hydraulic conductivity of 1.4×10^{-2} to 1×10^{-4} cm/s (UI80). Groundwater degradation occurs beyond the site boundary in the direction of Jefferson City.

Arsenic contamination has been detected up to 2900 feet from the tailings pond. A chemical analysis of sediments shows a decrease in contaminants with depth and distance from the tailings pond. Due to high levels of iron and manganese in the tailings pond (300 mg/L and 17 mg/L respectively), it appears that oxyhydroxides of these elements are readily formed and coprecipitate other heavy metals under governing chemical conditions in the host media. The sorption of cationic species by clay minerals as well as change in redox potential (Eh) and pH are other factors that control the migration distance of contaminants. Arsenic is the exception with the media effecting less control on its migration.

Fremont County, Wyoming

The Federal American Partners mill tailings pond located in the Gas Hills area of Fremont County, Wyoming, has leaked seepage to groundwater beneath the site. The unlined tailings pond is situated on weathered sandstone of the Wind River Formation. The acid-leach effluents have migrated approximately 3200 feet with chloride, sulfate, nitrogen, lead, and total dissolved solids found above background levels (UI80). Isoconcentration maps delineate the direction of migration of the contaminants with test data from 27 monitoring wells ranging in depth from 20 to 105 feet. Seepage migration appears to be confined to the deeper aquifer. Buried stream channels in the area could constitute zones of higher hydraulic conductivity so that groundwater migration could become greater without corrective action.

La Sal, Utah

The Rio Algom Corporation's Lisbon Valley mill tailings pond near La Sal, Utah, has seeped alkaline-leach process effluents to a perched groundwater mound in the vicinity of the tailings pond (UI80). The unlined pond is located on a thin layer of terrestrial deposits (10 feet or less) that overlie the Dakota-Burro Canyon sandstones. Contamination is restricted to the Dakota-Burro Canyon Formation with Drinking Water Standards exceeded approximately 1500 ft. away from the tailings ponds (UI80). Conclusions regarding the migration are based on isoconcentration maps for alkalinity (CO_3), chloride, nitrate sodium, sulfate, boron, total uranium, and radium-226. A major northwesterly-trending fault present near the site (3,000 ft. away) may influence the movement of the seepage plume at the site.

Milan, New Mexico

The Homestake uranium mill near Milan, New Mexico, has sustained 440 m^3/d or 6 percent seepage loss of alkaline-leach process effluents discharged to unlined tailings ponds (Ja79). The seepage has penetrated the highly permeable and saturated alluvium which blankets (up to 75 feet thick) the more massive, less permeable Chinli Formation bedrock of shale and sandstone (Pi81). A mound of contaminated groundwater underlies the tailings ponds, and elevated levels of uranium, radium, selenium, and nitrate-nitrogen, in excess of New Mexico Drinking Water Standards, have been found in surrounding wells used as drinking water by nearby residents (Pi81).

Selenium ranges up to 2.0 mg/L (limit is 0.05 mg/L); nitrate-nitrogen, up to 14.1 mg/L (limit is 10.0 mg/L); uranium, up to 5 mg/L (limit is 0.5 mg/L); radium-226, up to 9.5 picocuries/L (limit is 5.0 picocuries/L). Background levels and preoperational levels of selenium, nitrate, and sulfate have also at times exceeded New Mexico Drinking Water Standards. Such variations and potential faults beneath the tailings piles have made it difficult to determine the extent of contamination. Homestake is attempting to mitigate the groundwater pollution by pumping contaminated alluvial groundwaters back to tailings ponds and injecting better quality waters into the alluvium (Pi81). Some monitoring wells show water quality deterioration while others show improvement (UNHP80). The monitoring program in a complex hydrogeologic setting is compounded by potential faults which makes an assessment of the situation exceptionally difficult.

D.8 Control of Toxic Materials to Groundwater

Monitoring investigations of the migration pathways from unlined mill tailings pond have determined that radionuclides and some of the toxic heavy metals are attenuated within a few feet of the tailing pond but that some toxic heavy metals are highly mobile and have contaminated the groundwater. The mobile species include molybdenum, selenium, chlorine, sulfate, nitrate, arsenic, lead, and vanadium. Under existing hydrogeologic conditions and the chemical makeup of the seepage from the tailings pond, this condition prevails unless protective controls are utilized. Controls that exist to prevent groundwater contamination include, (a) complete containment by impervious seals (clay or synthetic liners), and/or (b) altering the chemistry of tailings pond effluents.

Clay and synthetic liners were mentioned earlier and are probably the most positive long-term controls for containment of both the acid-leach and alkaline-leach process effluents in tailings ponds. The long-term stability of earthen materials or clay liners in contact with acid tailings solutions has received extensive study by Pacific Northwest Laboratory (PNL) under NRC contract (Pe82). The highly acid condition of the acid-leach tailing effluents (1.8 pH) leach some of the clay. However, by laboratory testing the PNL investigation disclosed that materials that contained over 30 percent clay showed a decrease in permeability with time (Pe82).

The decreases in permeability for a number of clay materials considered were attributed to pore plugging resulting from the precipitation of minerals and solids. X-ray diffraction and geochemical predictions confirm that gypsum, jarosite, and other minerals precipitate after tailings solution reacts with the earth material comprising the liners (Pe82). To ensure that the initial permeability of the liner is minimized, the liner should be compacted to at least 90 percent of its maximum capacity as determined by a standard Proctor test (Pe82). A one-meter clay liner compacted with a calcium carbonate content of 4 percent or greater could be expected to impede the pH front advance into the surrounding geologic materials for hundreds of years and to neutralize the total acidity of a typical tailings pond (Pe82).

The concept of altering the chemistry of the uranium mill wastewater by precipitation to control the removal of toxic materials in tailings ponds has been investigated by the Environmental Protection Agency. This study was performed for both acid and alkaline waste streams and considered a number of processes. The most promising finding is the combining of acid waste streams with alkaline waste streams to precipitate metals that occur as anions (We80). Mobile metals, such as Mo and V, present in anionic form as molybdates and vanadates, are effectively removed from solution at a pH range of 5.8 to 6.1 achieved by mixing the acid and alkaline mill waste at a 5:3 ratio by volume (We80). Other metals largely removed at this pH include iron, aluminum, chromium, and nickel. However, few alkaline-process mills and acid-process mills are located close enough to accomplish this mixing.

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